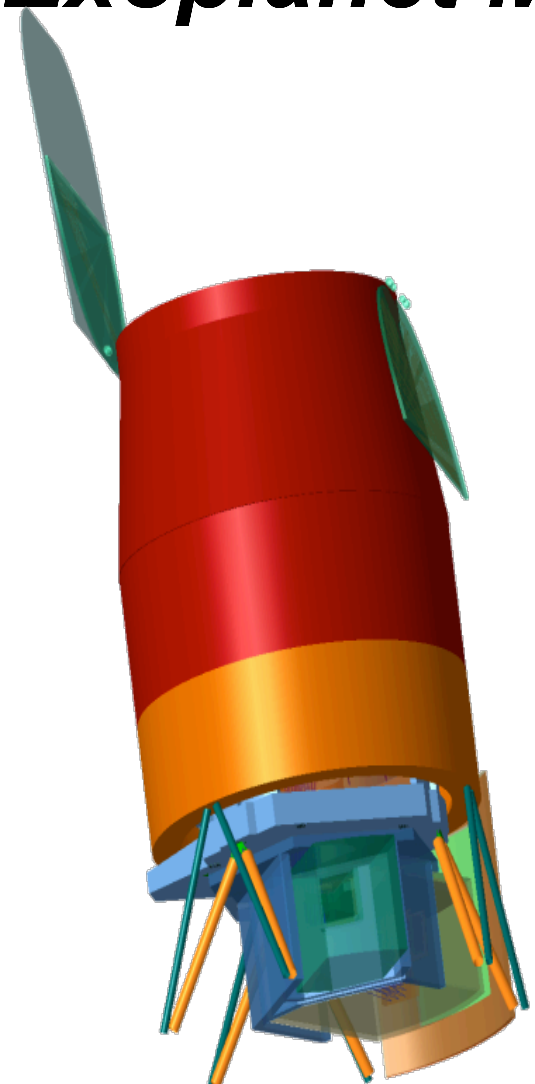
WFIRST-AFTA
Exoplanet Microlensing Preparations



David Bennett
University of Notre Dame

ExoPAG SAG-11 Report

NASA ExoPAG Study Analysis Group 11:

Preparing for the WFIRST Microlensing Survey

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- Led by Jennifer Yee
- Not a detailed study, but a description of several important precursor programs

Recommended Precursor Observations

- HST precursor observations
  - HST/WFC3/UVIS + ACS observations for pre-WFIRST astrometry
  - HST/WFC3/IR time series observations for photometry/ astrometry pipeline code development
- Ground-based IR microlensing survey to measure lensing rate and select WFIRST-AFTA fields
- Development of Microlensing Expertise
  - HST and AO follow-up of current planet detections
  - Kepler (K2) and Spitzer parallaxes
  - Develop microlensing analysis methods
    - 1 (out of ~50) ground-based planetary light curve not modeled
    - Possibly many stellar binary + planet light curves not recognized

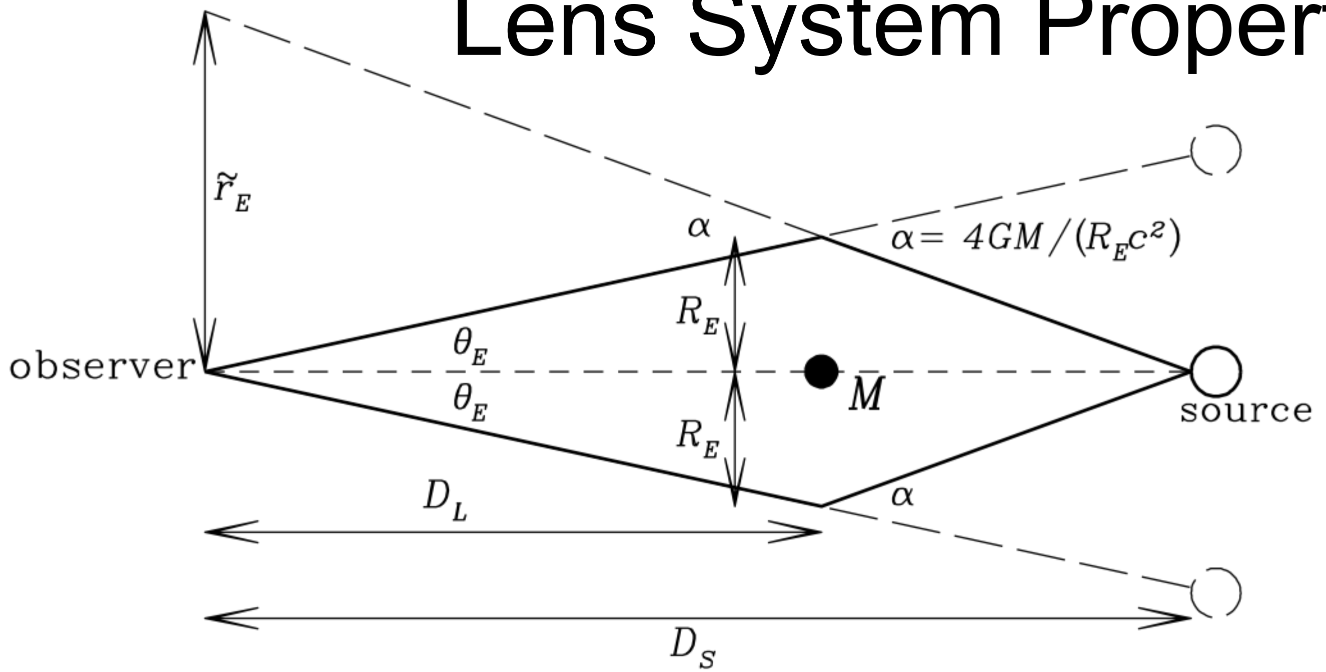
Lens System Mass and Distance from Microlensing Light Curves

- binary lens light curve gives mass ratio, q, and separation, s (in units of R_E)
- t_E depends on M_L, but also on $v_\perp$ and D_L

$$t_E = R_E / v_\perp \quad \text{where} \quad R_E = \sqrt{4GM_L D_S x(1-x)/c^2} \quad \text{and} \quad x = D_L / D_S$$

- There are two ways to improve upon this with light curve data:
  - Planetary light curves usually give source radius crossing time, t_*
  - Determine the angular Einstein radius : $\theta_E = \theta_* t_E / t_* = t_E \mu_{rel}$ where θ_* is the angular radius of the star and μ_{rel} is the relative lens-source proper motion
  - Measure the projected Einstein radius, $\tilde{r}_E$, with the microlensing parallax effect (due to Earth's orbital motion).

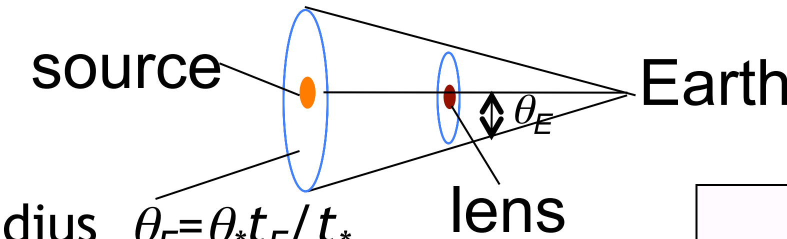
Lens System Properties



- Einstein radius : $\theta_E = \theta_* t_E / t_*$ and projected Einstein radius, $\tilde{r}_E$
  - θ_* = the angular radius of the star
  - $\tilde{r}_E$ from the microlensing parallax effect (due to Earth's orbital motion).

$$R_E = \theta_E D_L, \text{ so } \quad \alpha = \frac{\tilde{r}_E}{D_L} = \frac{4GM}{c^2 \theta_E D_L}. \text{ Hence } M = \frac{c^2}{4G} \theta_E \tilde{r}_E$$

Finite Source Effects & Microlensing Parallax Yield Lens System Mass



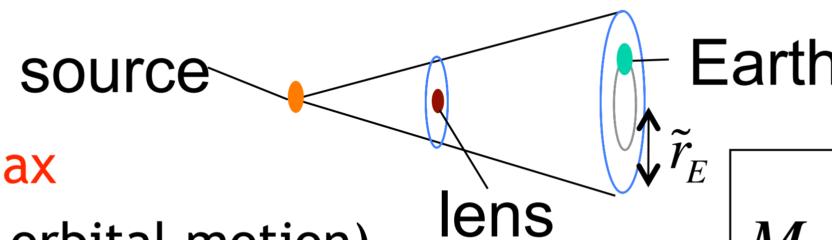
- Finite source effects

  Angular Einstein radius $\theta_E = \theta_* t_E / t_*$

  θ_* = source star angular radius

  D_L and D_S are the lens and source distances

$$M_L = \frac{c^2}{4G}\theta_E^2 \frac{D_S D_L}{D_S - D_L}$$



- Microlensing Parallax

  (Effect of Earth's orbital motion)

  Einstein radius projected to Observer $\tilde{r}_E$

$$M_L = \frac{c^2}{4G}\tilde{r}_E^2 \frac{D_S - D_L}{D_S D_L}$$

OR

- One of above +

  Lens brightness & color(AO,HST)

  mass-distance relation → D_L

$$M_L = \frac{c^2}{4G}\tilde{r}_E \theta_E$$

Finite Source Effects & Microlensing Parallax Yield Lens System Mass

- If only θ_E or $\tilde{r}_E$ is measured, then we have a mass-distance relation.
- Such a relation can be solved if we detect the lens star and use a mass-luminosity relation
  - This requires HST or ground-based adaptive optics
- With θ_E, $\tilde{r}_E$, and lens star brightness, we have more constraints than parameters

mass-distance relations:

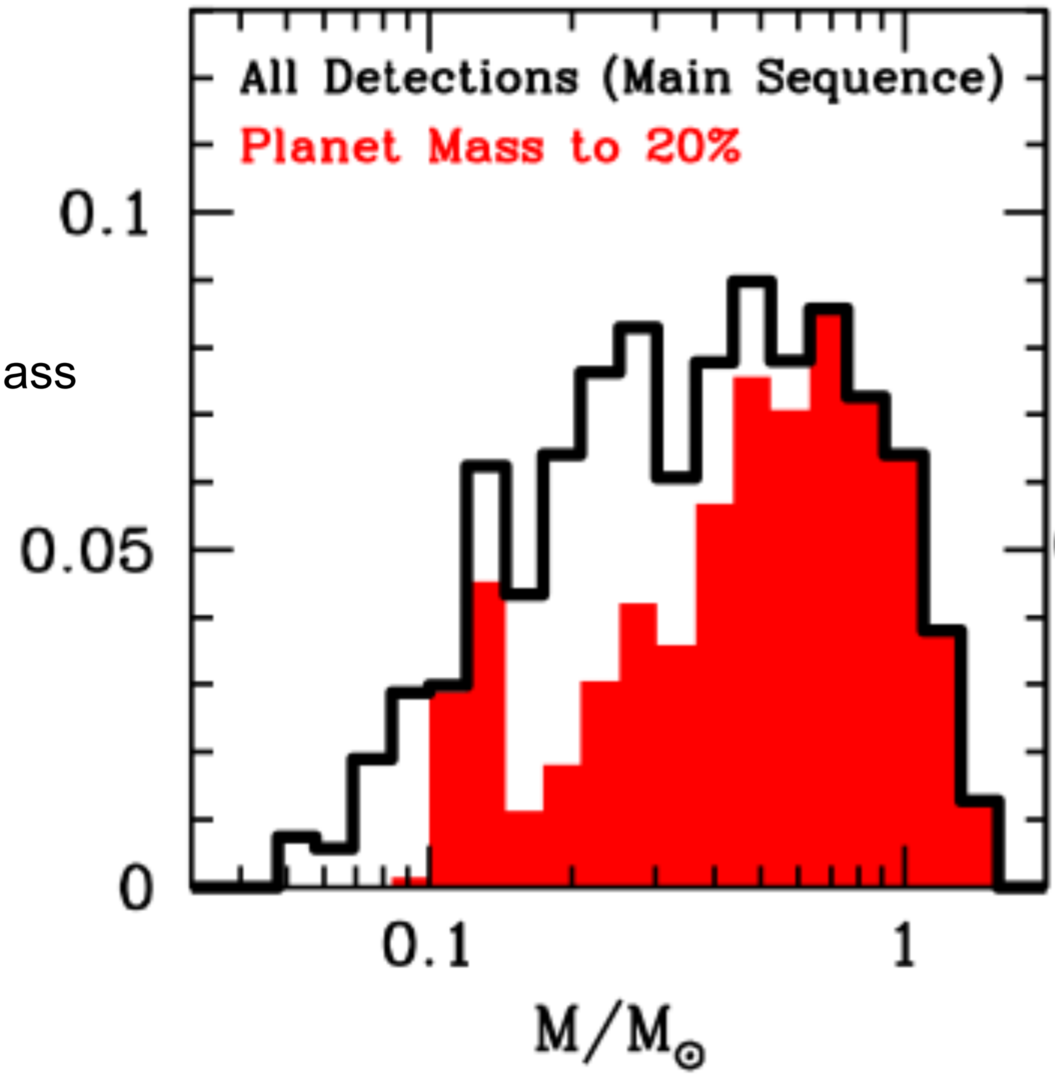
$$M_L = \frac{c^2}{4G}\theta_E^2 \frac{D_S D_L}{D_S - D_L}$$

$$M_L = \frac{c^2}{4G}\tilde{r}_E^2 \frac{D_S - D_L}{D_S D_L}$$

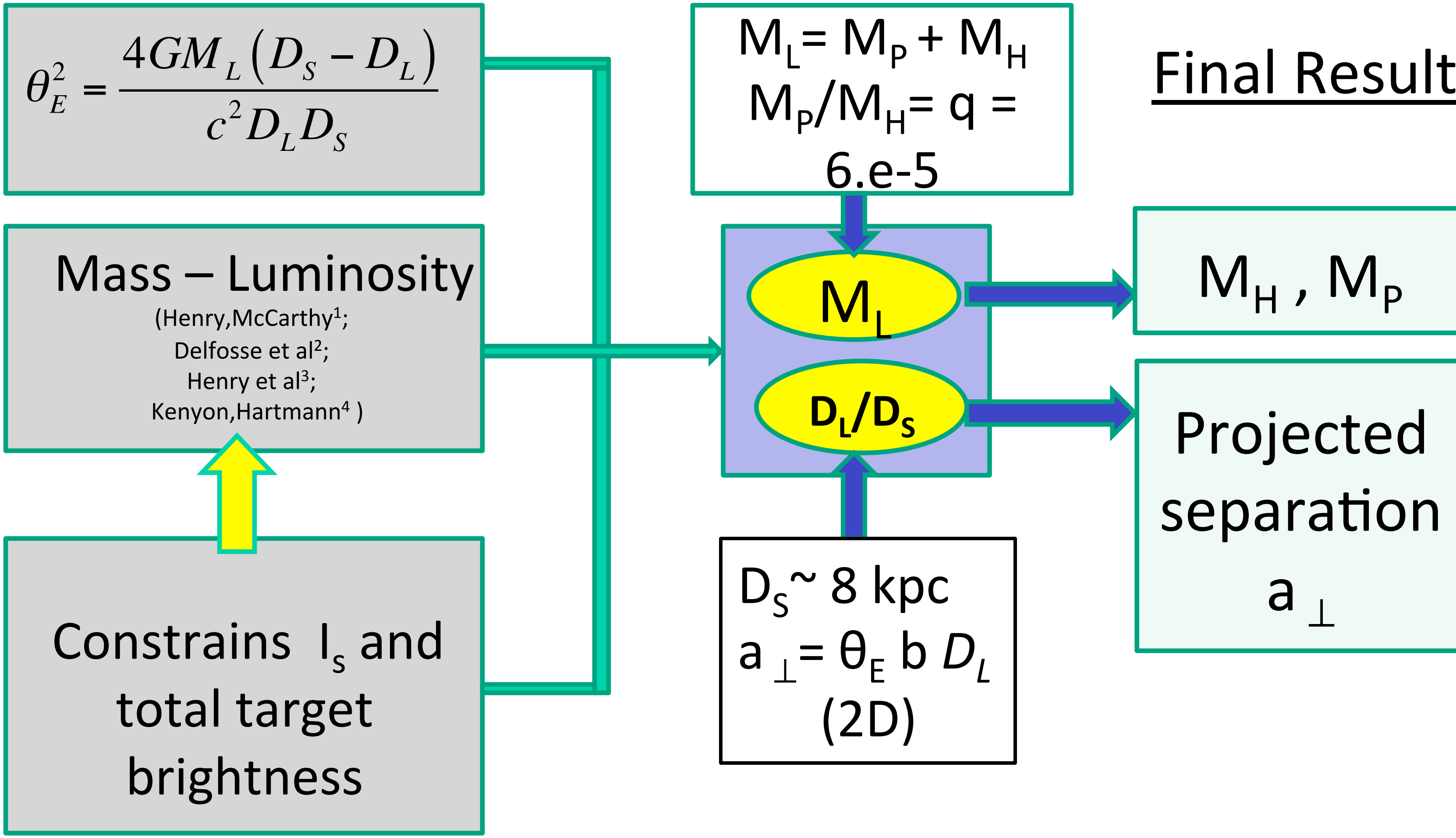
$$M_L = \frac{c^2}{4G}\tilde{r}_E \theta_E$$

Bright Lens Stars Detected in WFIRST Frames

- The brightness of the lens can be combined with a mass-luminosity relation to yield the lens system mass
- The direction of the $\mu_{\rm rel}$ helps determine $|\pi_E|$
- Masses of faint lens stars, brown dwarfs and stellar remnants are harder to determine.



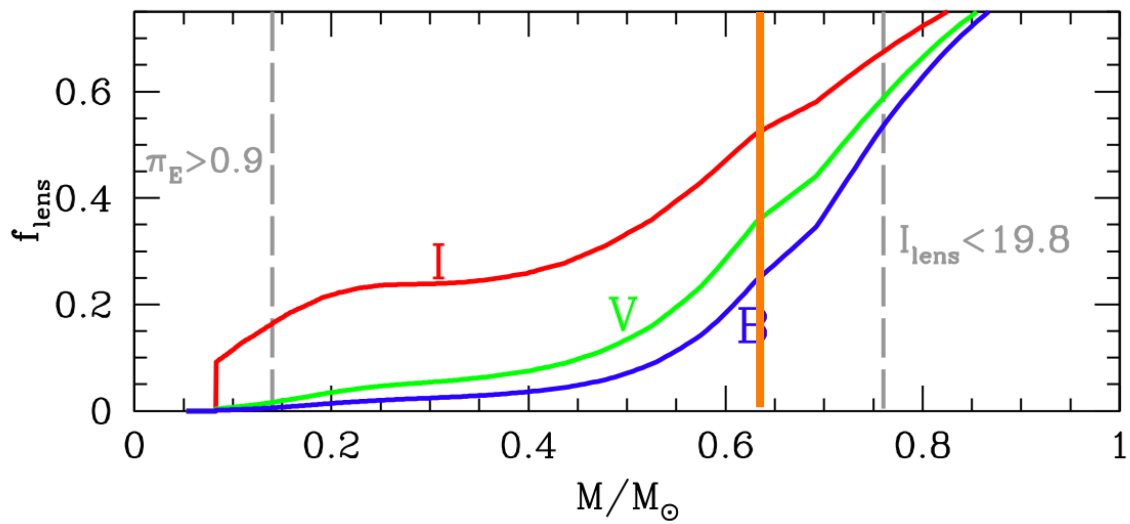
Determination of Host Star and Planet Mass

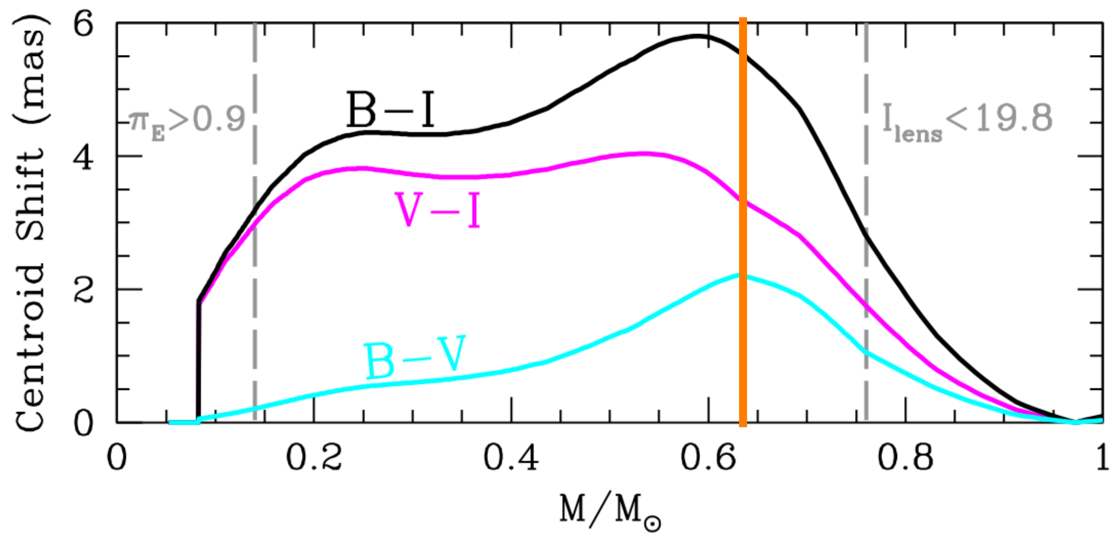


1. Henry and McCarthy (1993, AJ, 106, 773)
2. Delfosse et al (2000 A&A 364, 217)
3. Henry et al (1999, ApJ, 512, 864)
4. Kenyon and Hartmann (1995, ApJS, 101, 117)

Lens+Source Solution:

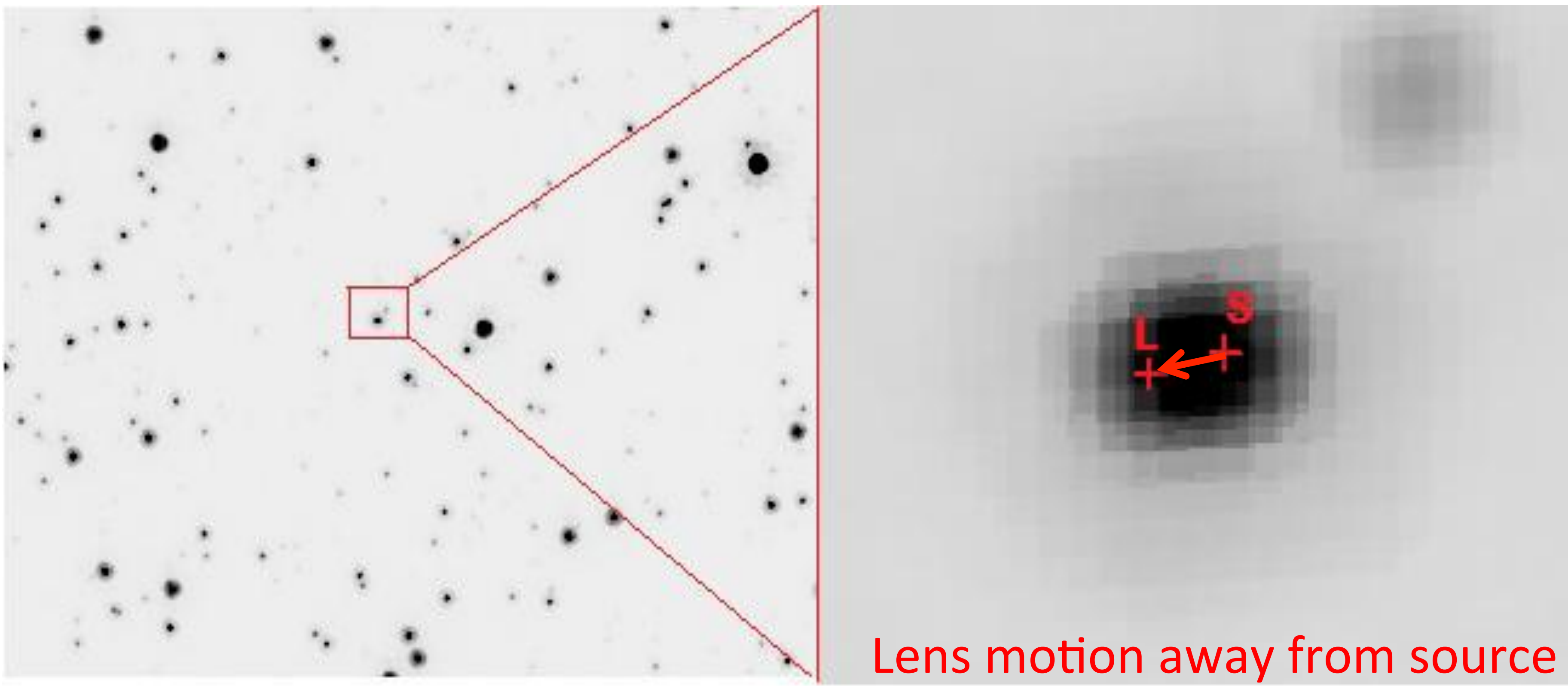
- Lens brightness vs. mass prediction (from Bennett, Anderson & Gaudi 2007)
- I-band flat spot at $M \sim 0.3M_\odot$
- Resolved with multiple colors
  - A bluer passband might help





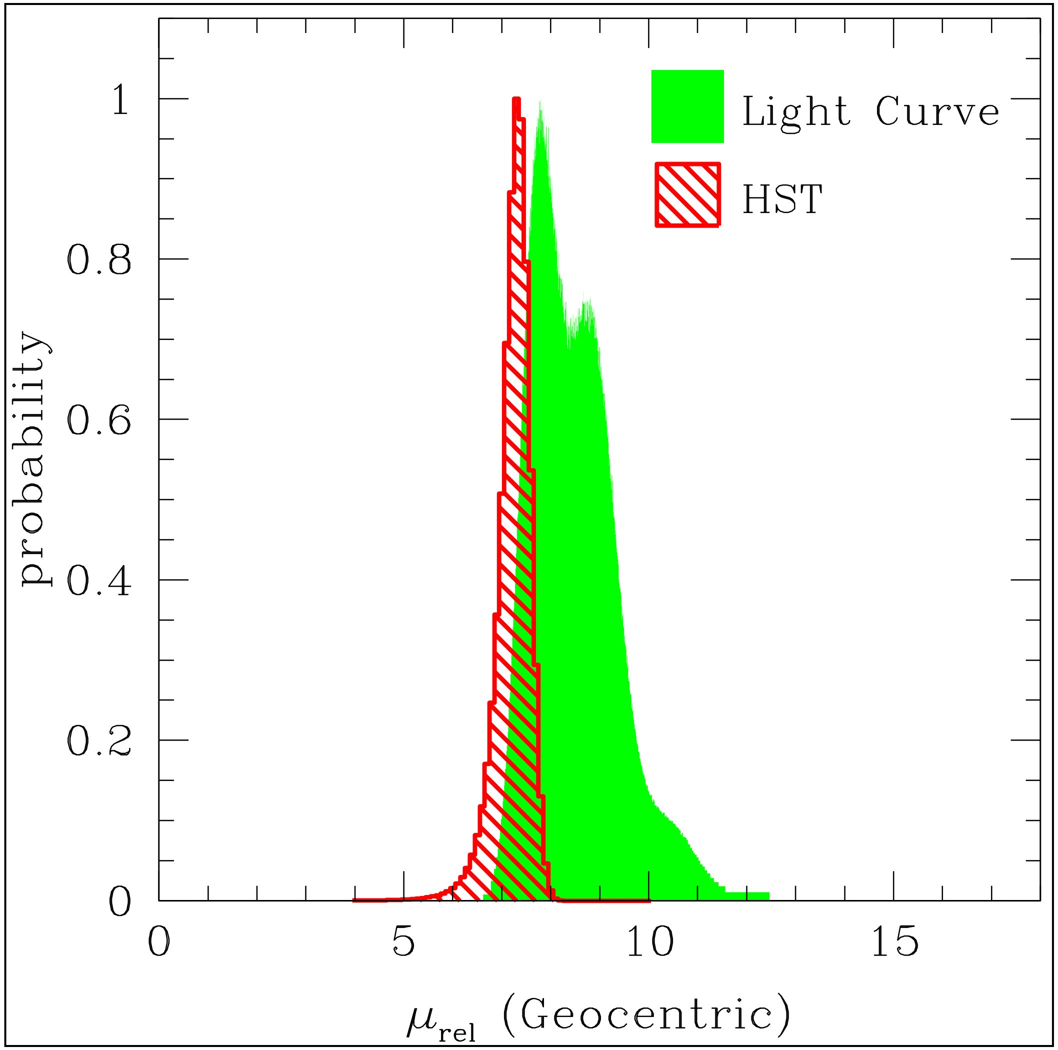
Demonstration of WFIRST Mass Measurement Method

HST image of OGLE-2005-BLG-169Lb – 6.5 years after discovery



Motion easily detectable after 2.5 years, but HST TAC not cooperative until 6.5 years (Bennett et al, in preparation)

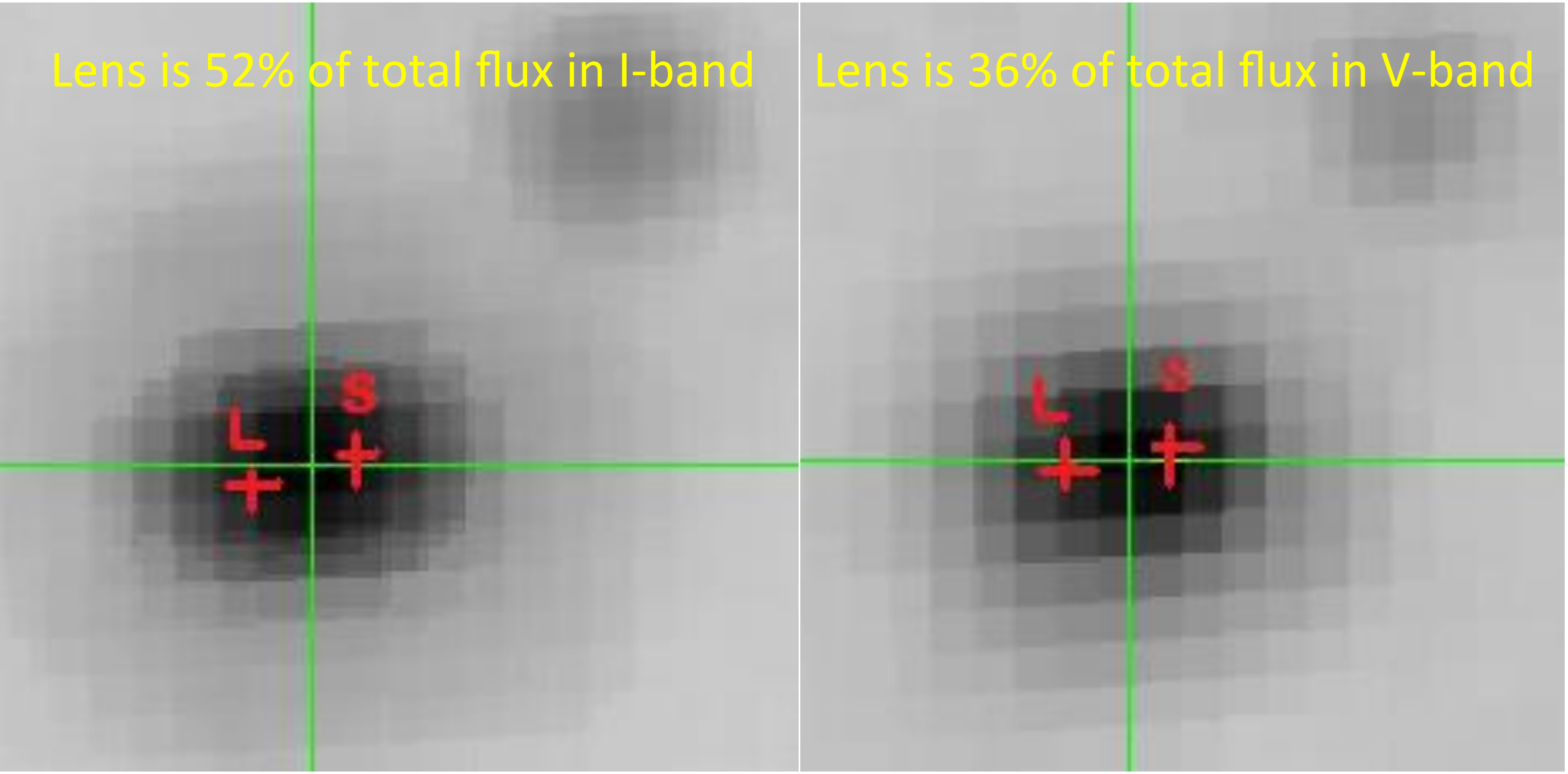
Lens-Source Relative Proper Motion from Planetary Signal Confirmed



- μ_{rel} from light curve
- μ_{rel} = 7.2 ± 0.4 mas/yr from HST
- First Confirmation of Microlens Planet Signal
- M_{host}= 0.687 ± .021 $M_{\odot}$
- M_{planet} = 14.1 ± 0.9 $M_{\oplus}$
- D_L = 4.1 ± 0.4 kpc
- $a_{\perp}$= 3.5 ± 0.3 AU (projected separation)

Aparna Bhattacharya

HST Observations & PSF Fitting

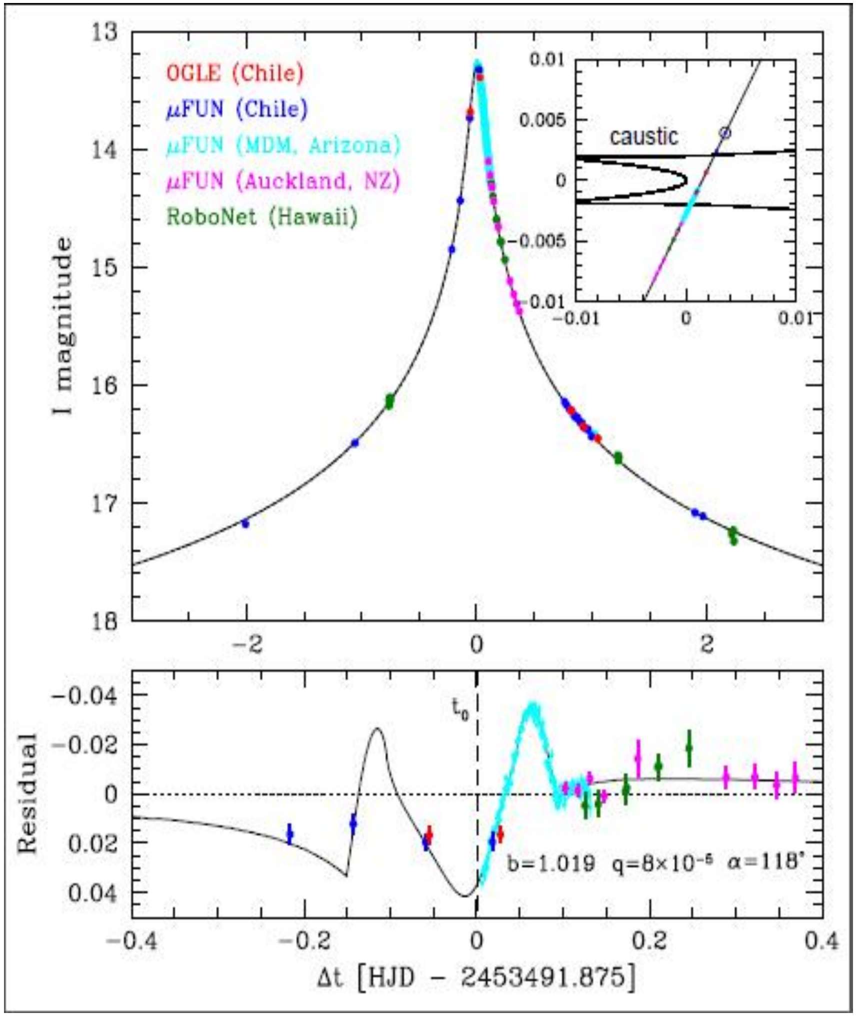


Centroid shift implies Source star has higher flux ratio

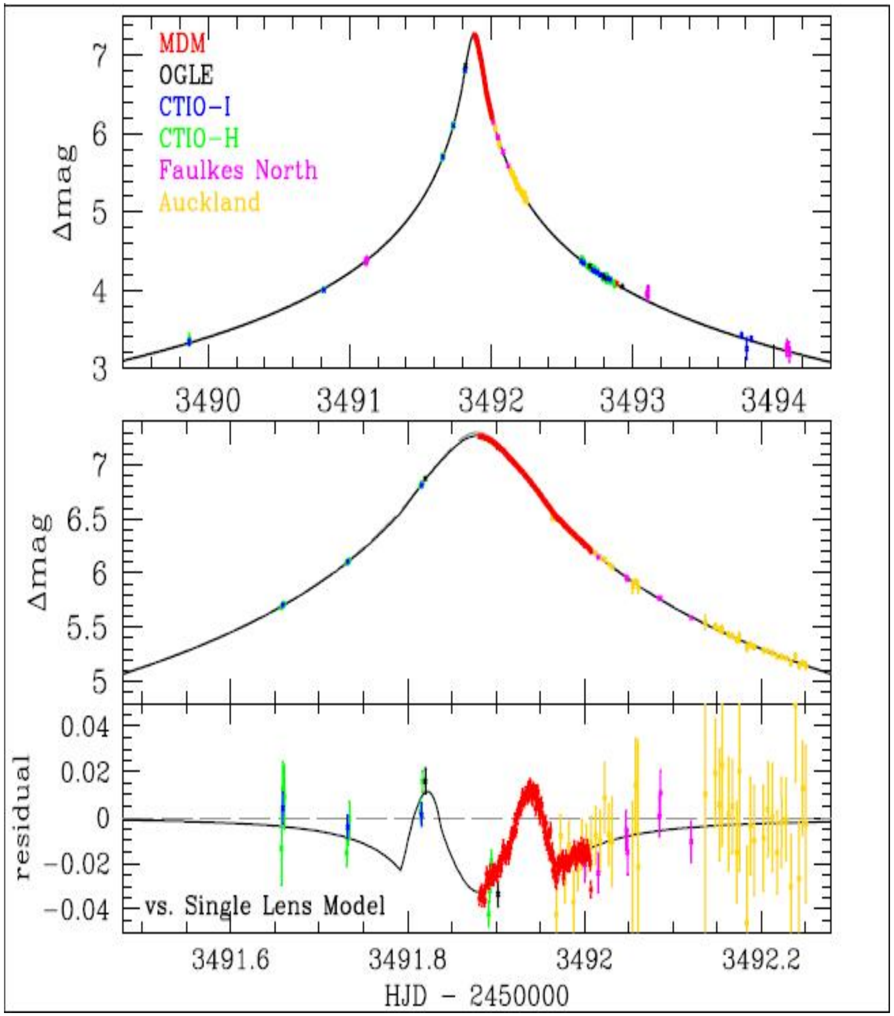
Aparna Bhattacharya

Light Curve Models

Discovery paper light curve[1]



Light curve consistent with HST



1. **Gould et al (2006, ApJ, 644, L37)**

High Angular Resolution Follow-up

- Lens-source relative proper motion signal of $\boldsymbol{\mu}_{rel}$ was strong for OGLE-2005-BLG-169
- WFIRST-AFTA will have a smaller time baseline (< 6.5 years) and larger PSF but many more observations
- To predict WFIRST-AFTA performance, we need to understand the systematic errors
- Current HST program has 4 more targets to be analyzed, but there are 40 more that could be observed.

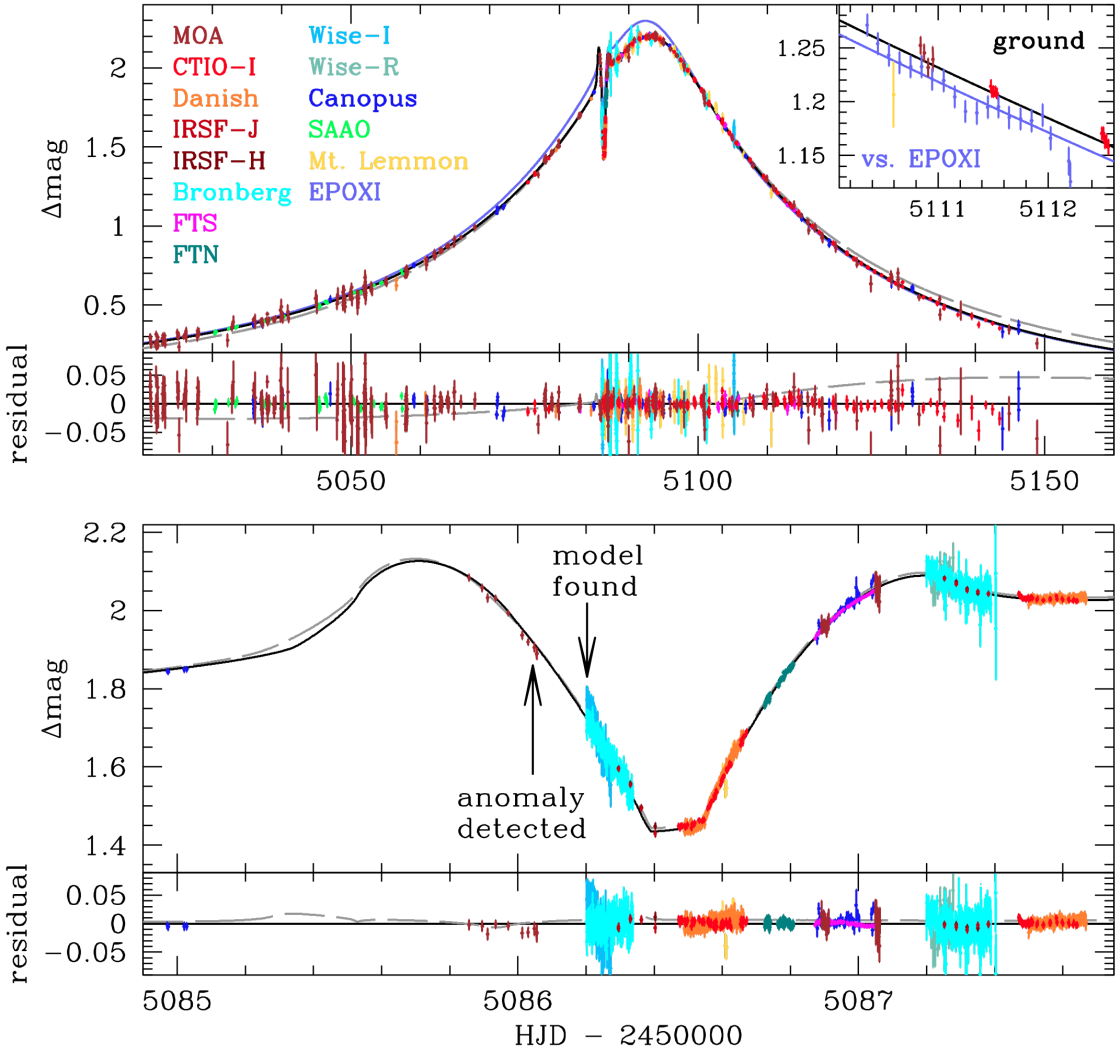
Parallax and Relative Proper Motion or Astrometric Microlensing

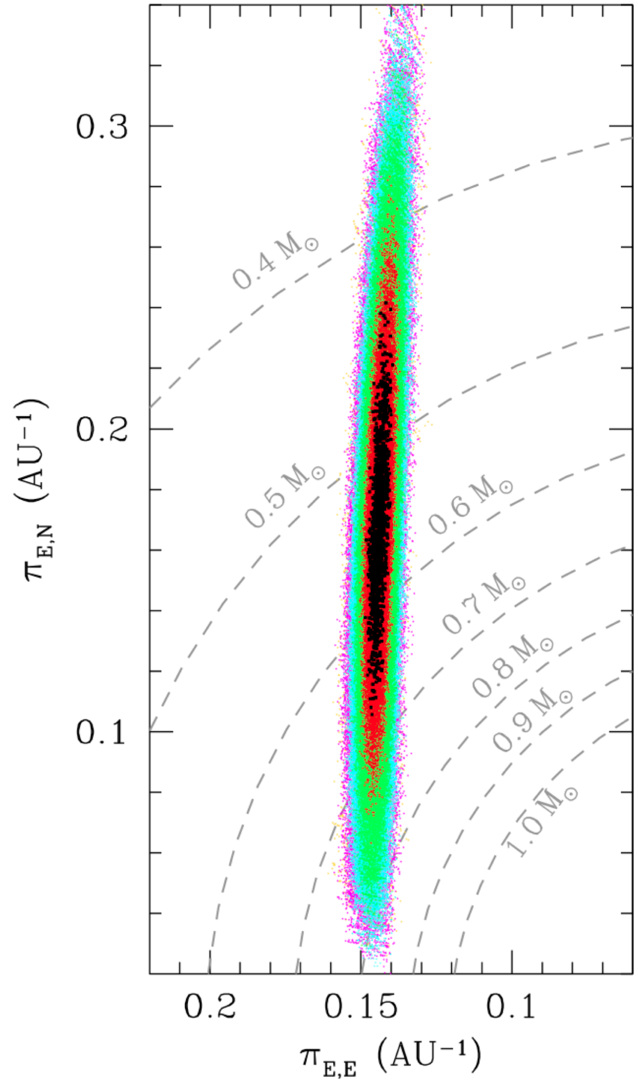
- Microlensing parallax $\pi_E = \dfrac{1}{\tilde{r}_E}$ and
- relative proper motion $\mu_{\mathrm{rel}} = \dfrac{\theta_E}{t_E} = \dfrac{\theta_*}{t_*}$

- are both 2-d vectors – and they are parallel
- π_E is often measured more precisely in 1 direction (Earth's acceleration direction) than the other
- A measurement of $\boldsymbol{\mu}_{\mathrm{rel}}$ improves the precision of $|\pi_E|$

- Astrometric microlensing yields the same information as $\boldsymbol{\mu}_{\mathrm{rel}}$: θ_E and direction of lens-source motion

MOA-2009-BLG-266 Orbital Parallax



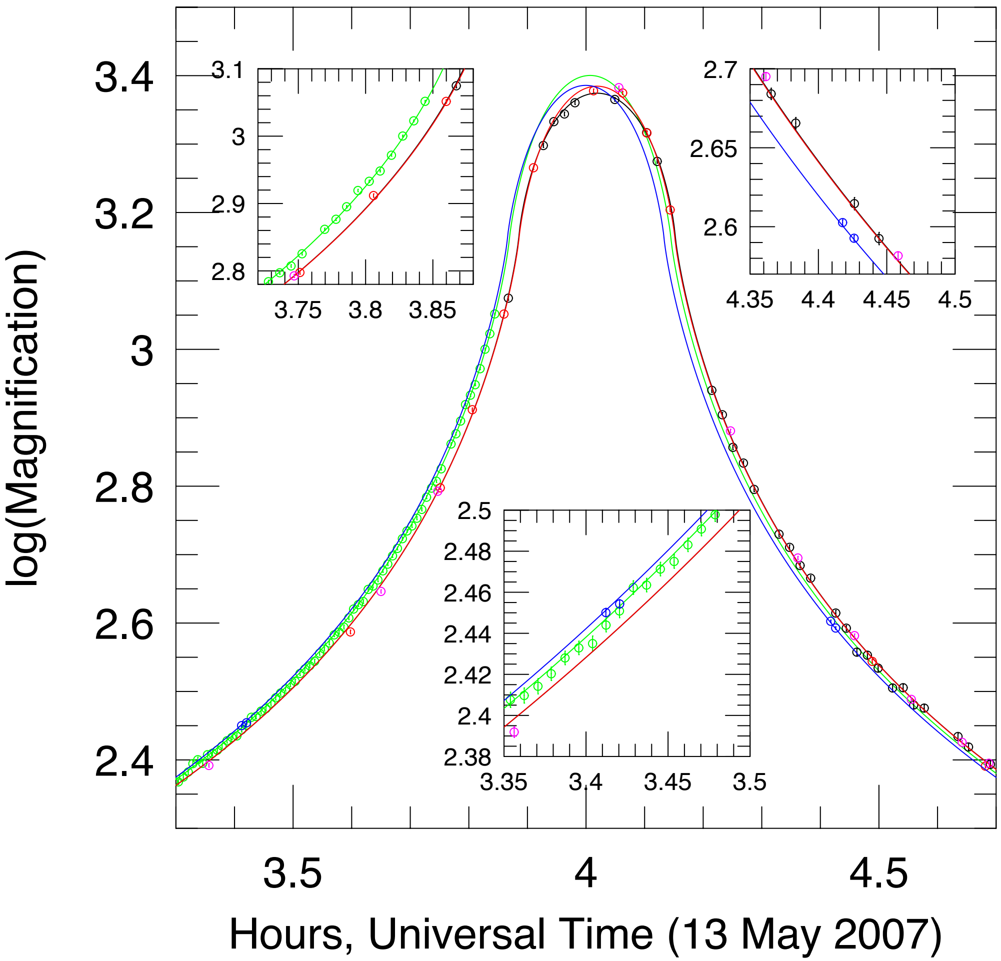


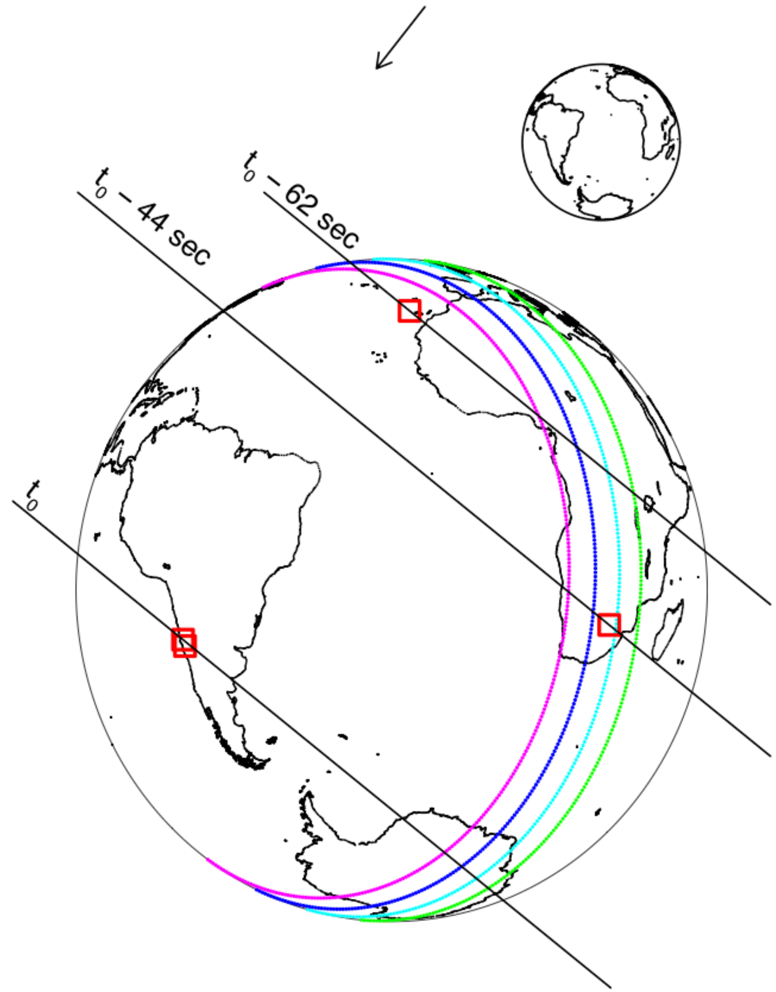
$m_p = 10.4 \pm 1.7 M_\oplus$ $\quad M_* = 0.56 \pm 0.09 M_\odot$

$a = 3.2^{+1.9}_{-1.5}$ AU $\quad D_L = 3.0 \pm 0.3$ kpc

The bulge is near the ecliptic plane so parallax uncertainty is asymmetric

Terrestrial μlensing Parallax Measures Masses



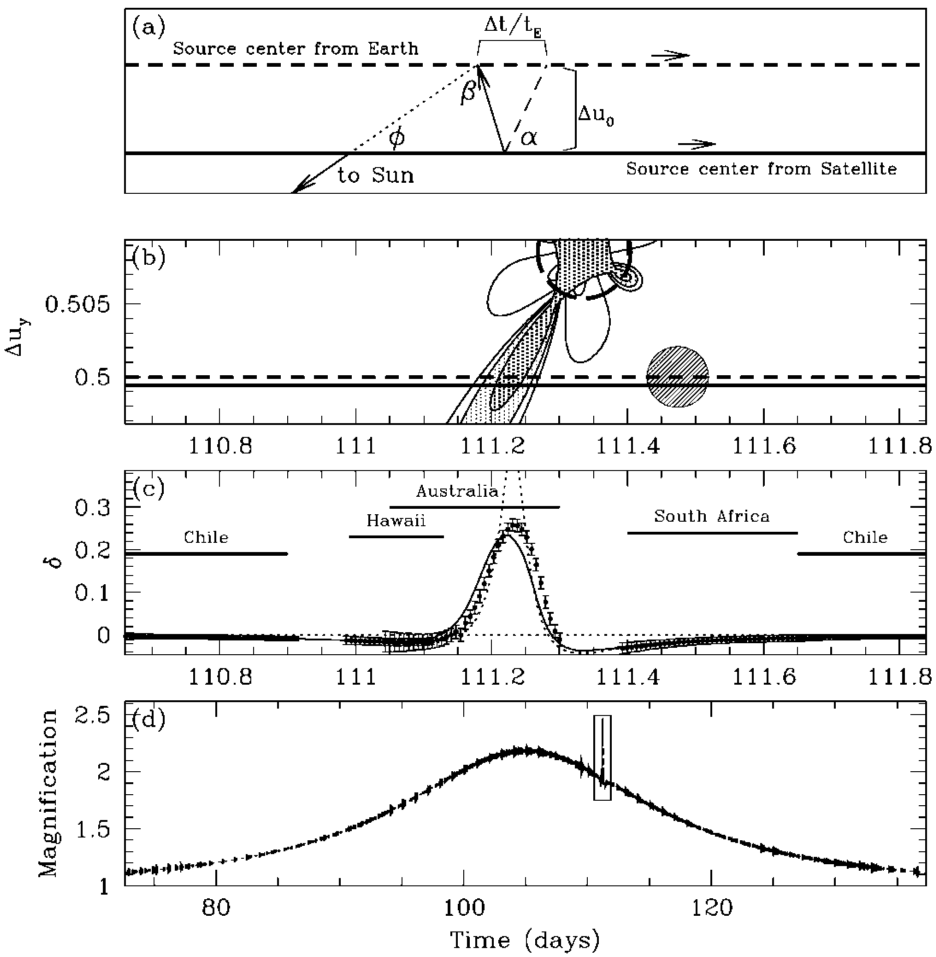


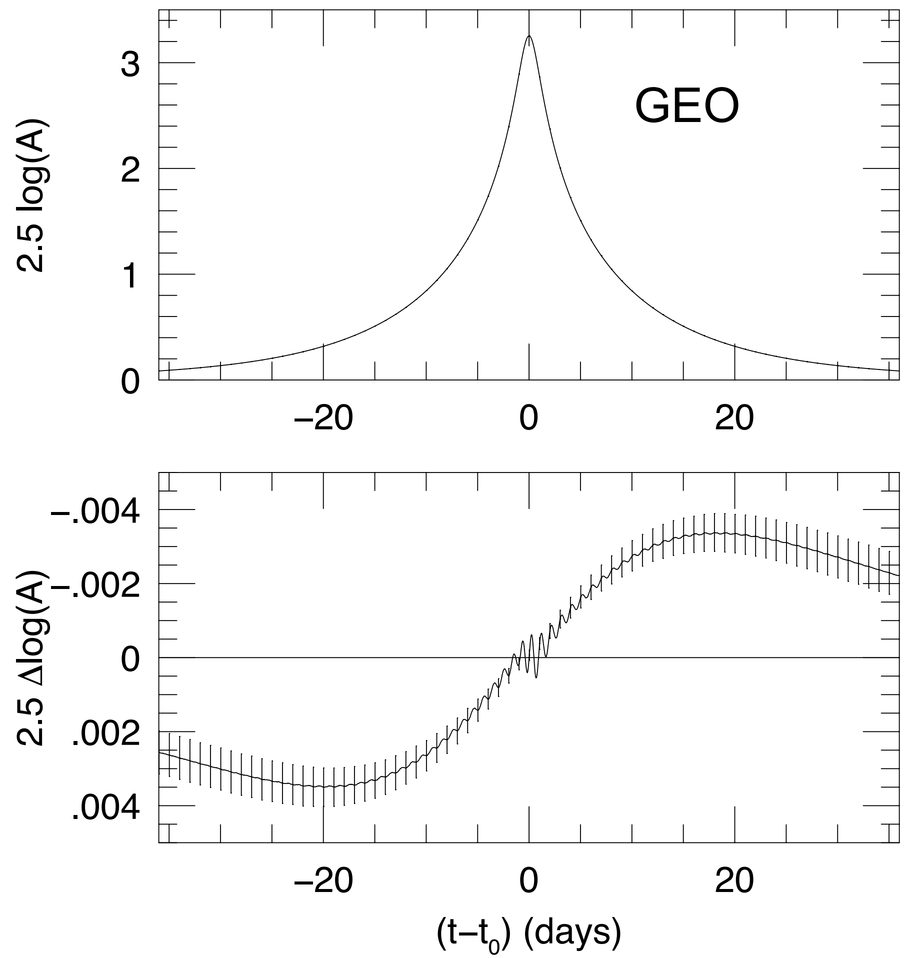
OGLE-2007-BLG-224L mass, $M_L = 0.056 \pm 0.004\ M_\odot$ (Gould et al. 2009)

$D_L = 525 \pm 40$ pc and $v_\perp = 113 \pm 21$ km s^{-1}

Multi-site observations needed!!

Geosynchronous vs. L2 Microlensing Parallax

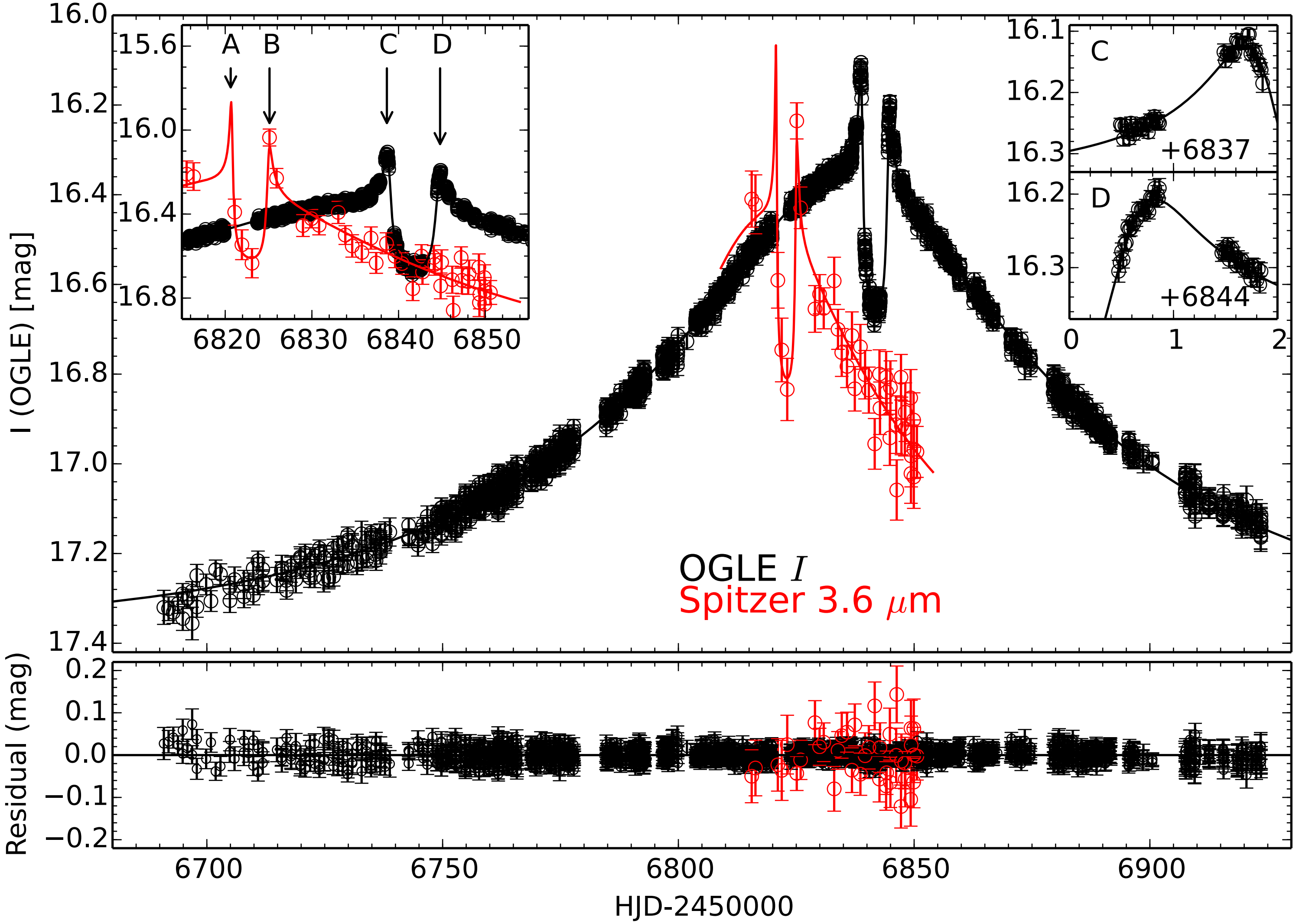




L2 gives parallax from planetary signals if they can be detected from the ground (Gould, Gaudi & Han 2003)

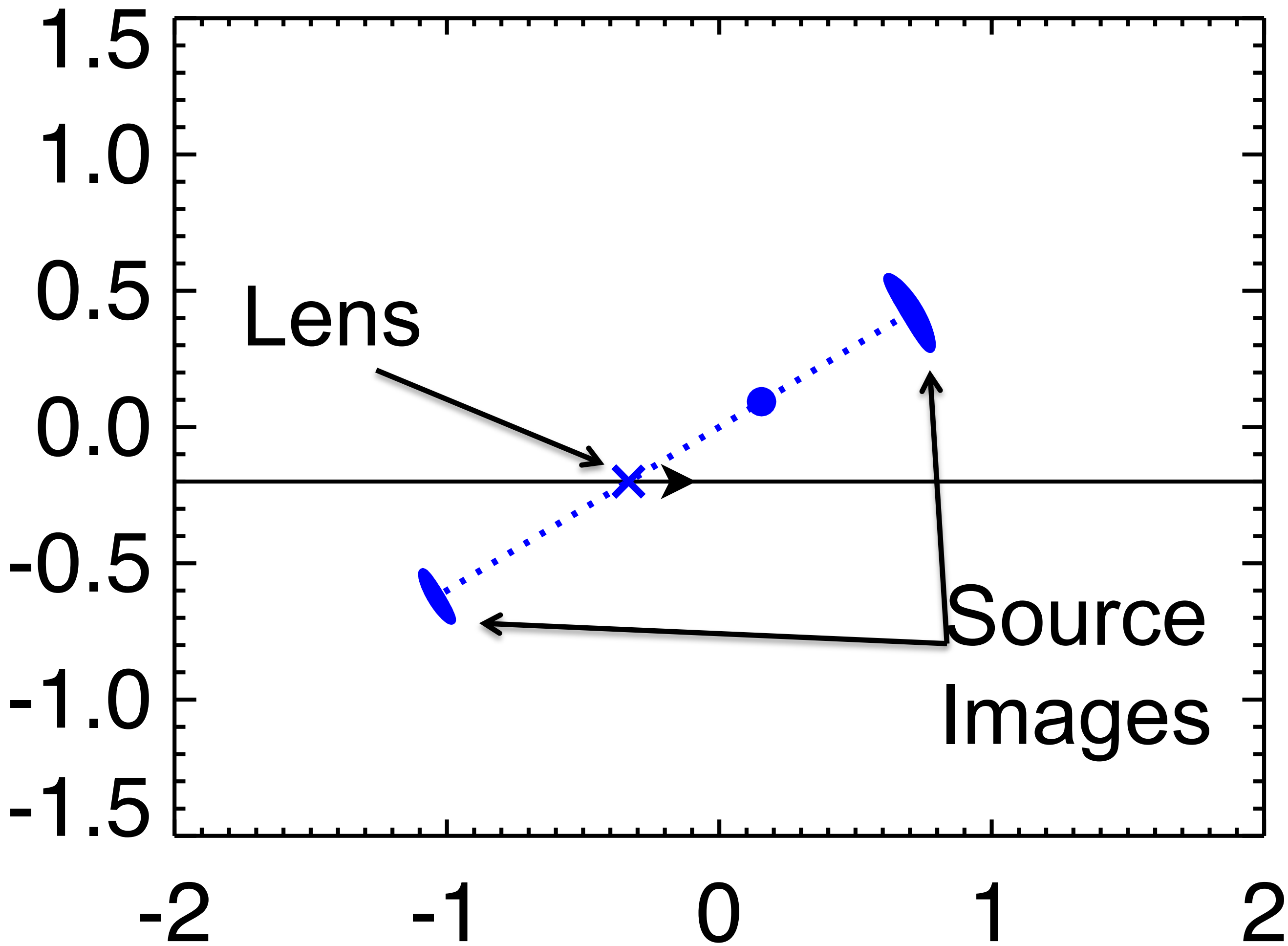
GEO gives parallax small signals from high-mag events (Gould 2013)

Spitzer & OGLE observations of OGLE-2014-BLG-0124

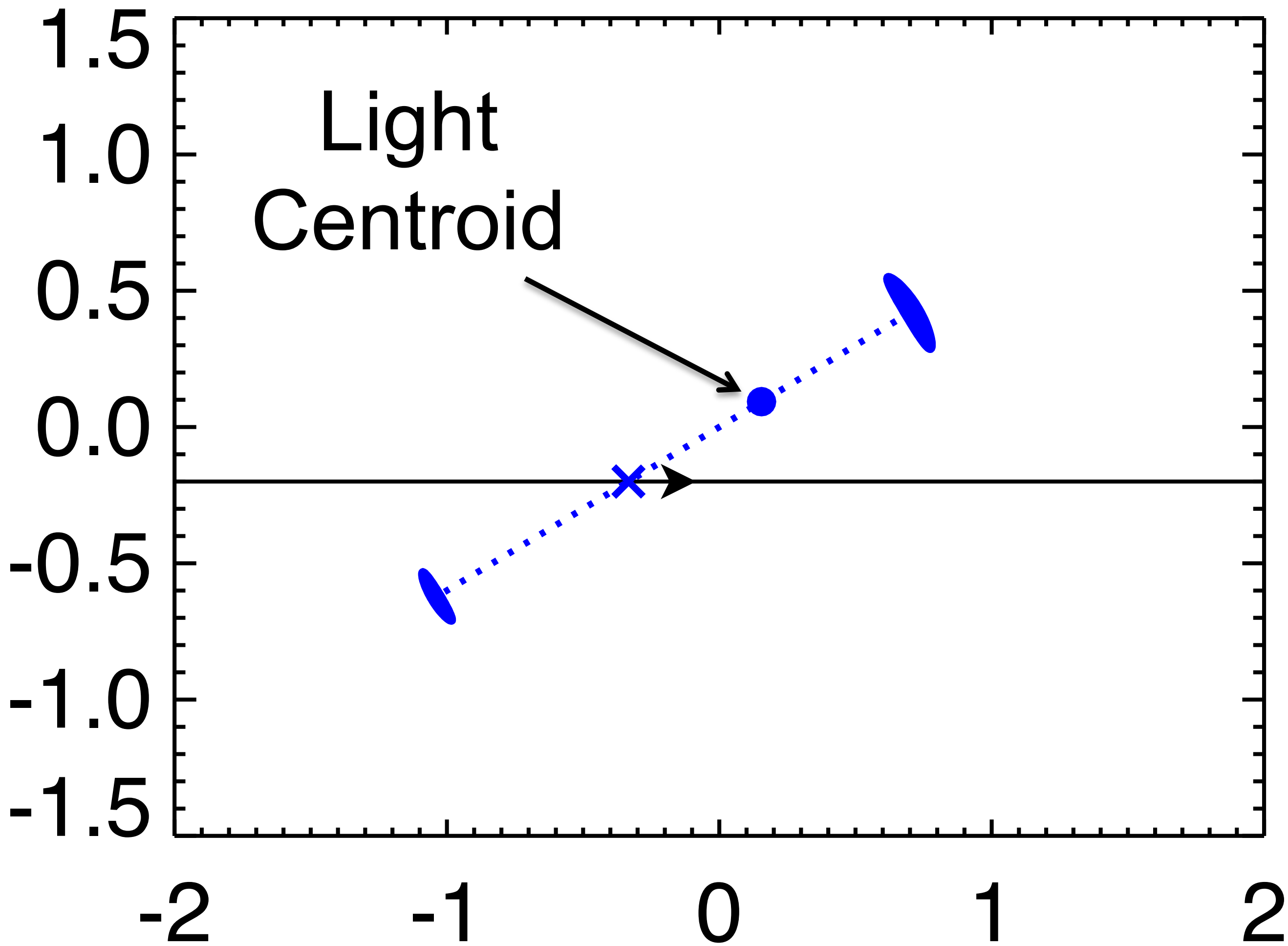


Udalski et al. 2014, ApJ, submitted, arXiv: 1410.4219

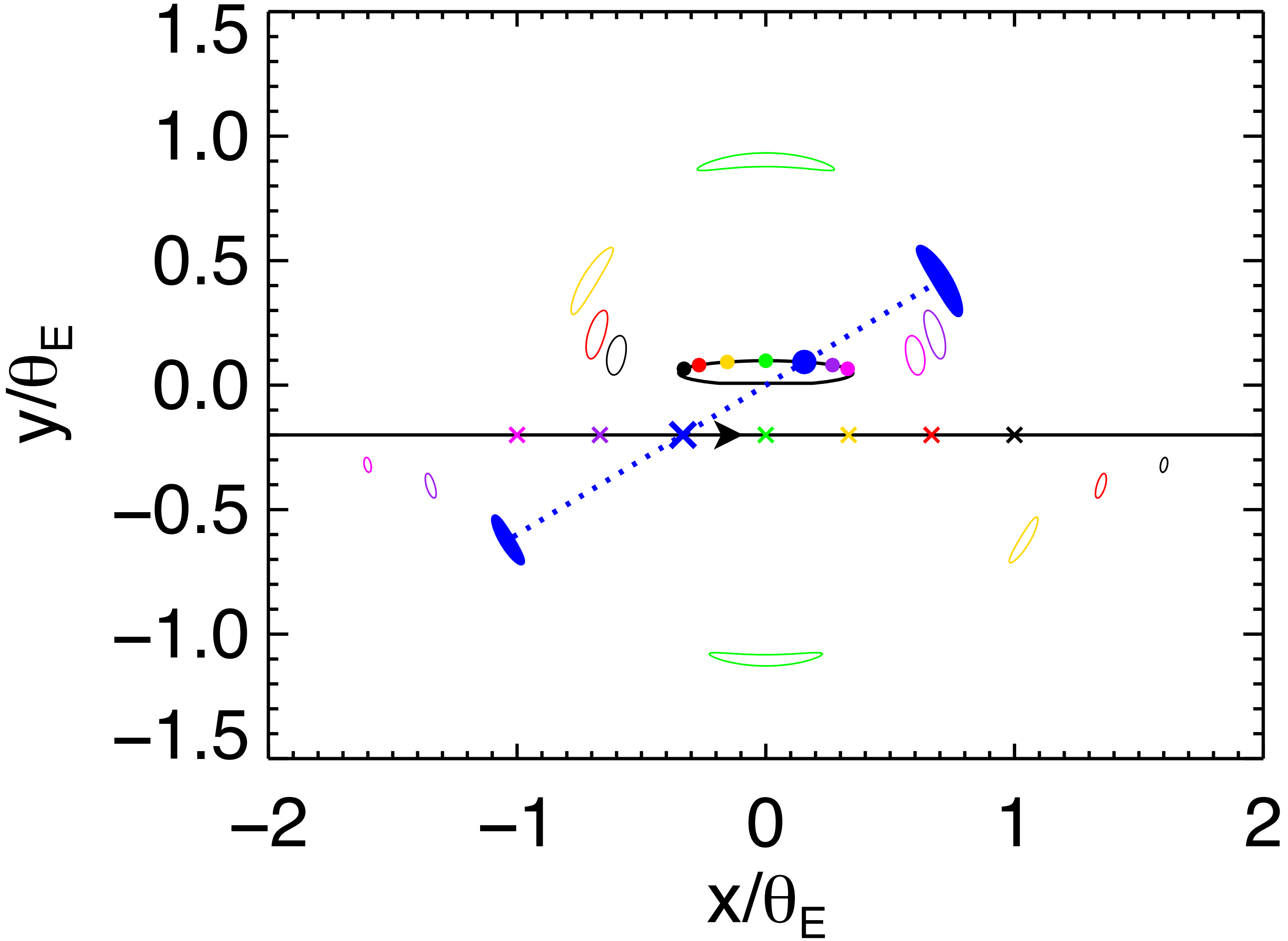
Astrometric Microlensing



Astrometric Microlensing

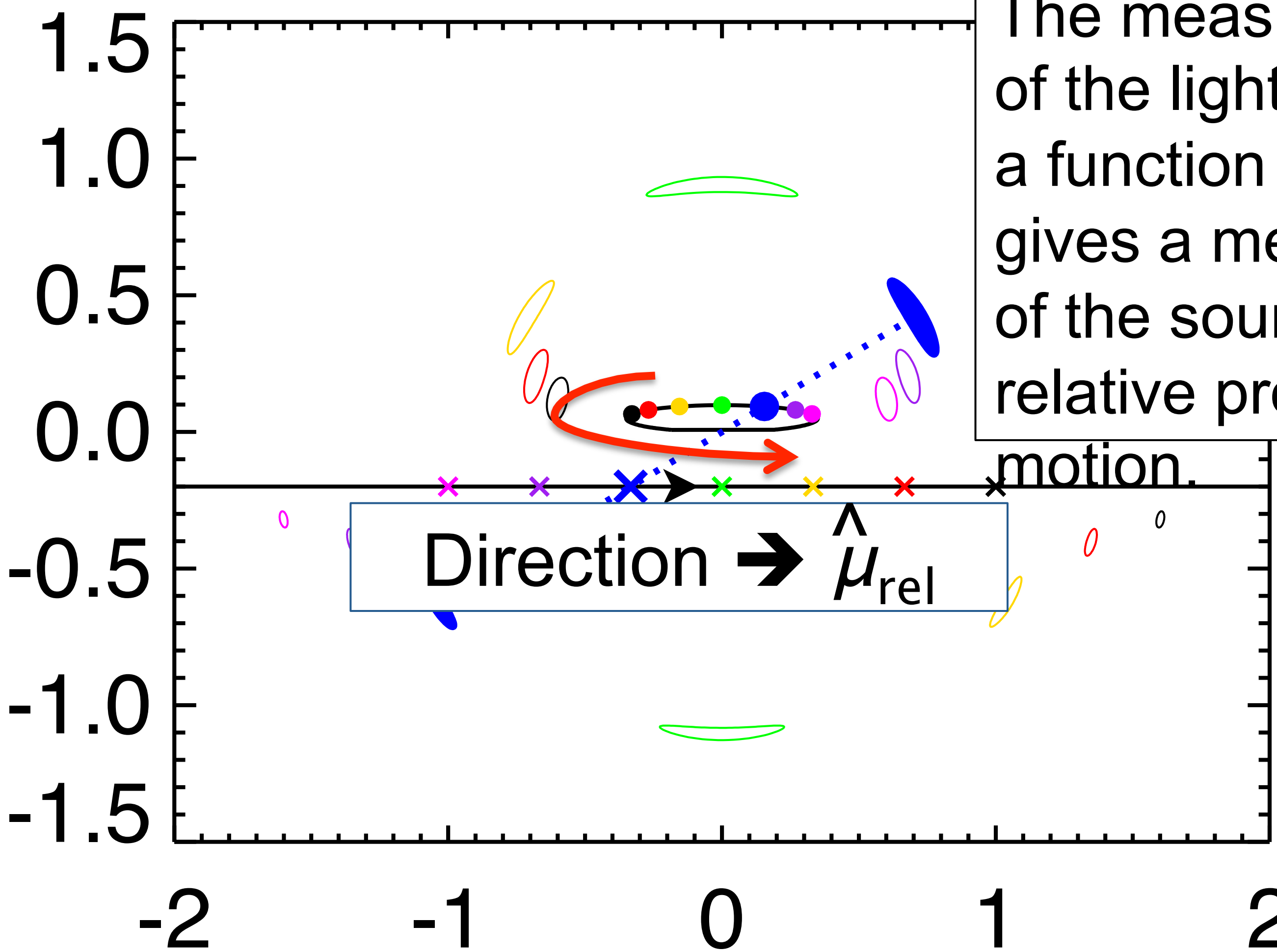


Astrometric Microlensing



Centroid motion is small (~0.1 mas) except for black hole lenses (i.e. Sahu HST programs). Needed for dark lenses without finite source effects – stellar remnant mass function. Long time baseline needed for a precise measurement – we need to know the source proper motion to high precision.

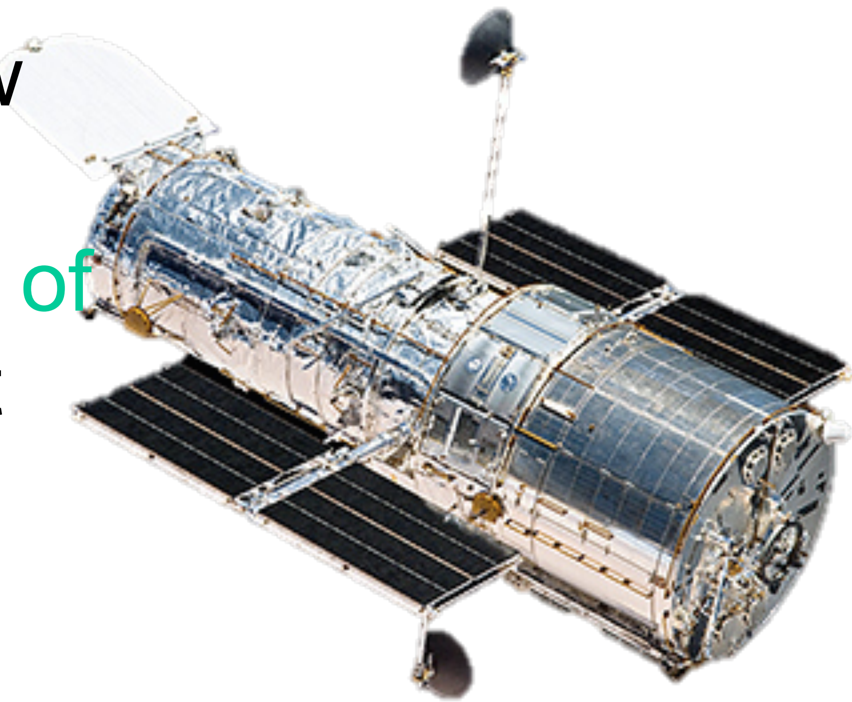
Astrometric Microlensing



The measured motion of the light centroid as a function of time gives a measurement of the source-lens relative proper motion.

Optical HST Imaging

An immediate, optical HST survey of the WFIRST fields will allow proper motion measurements for 22% of WFIRST stars → Direct verification of WFIRST microlens astrometry.

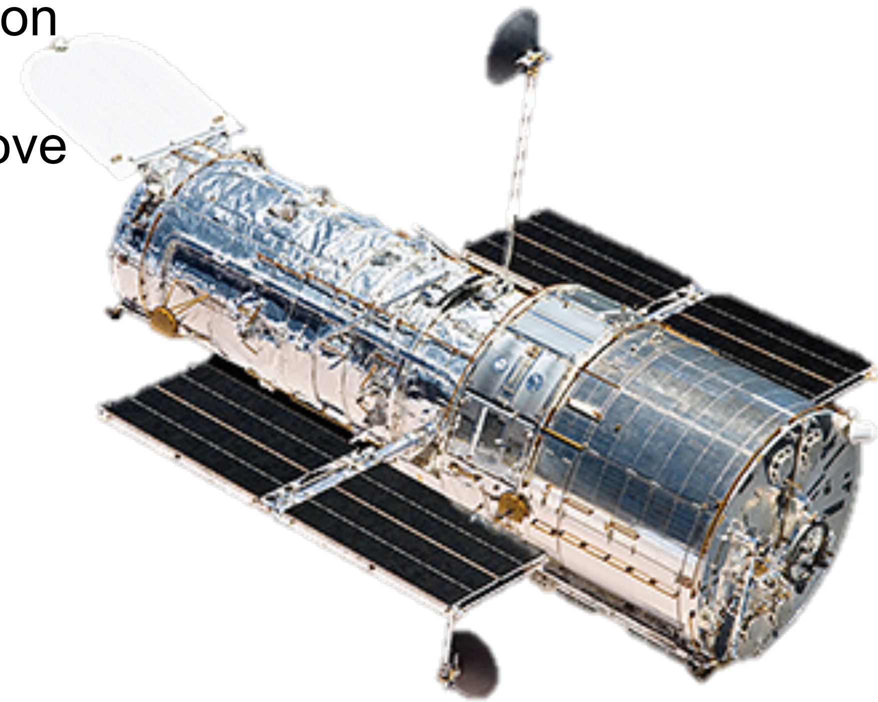


Reliable microlens astrometry measurements are vital to measuring planet masses with WFIRST.

Optical HST Imaging

- Early measurements provide precision test for WFRIST astrometry
- Long time baseline will greatly improve astrometric microlensing measurements (critical for stellar remnant mass measurements)
- Develop WFIRST exoplanet mass measurement method
- Help select HST fields

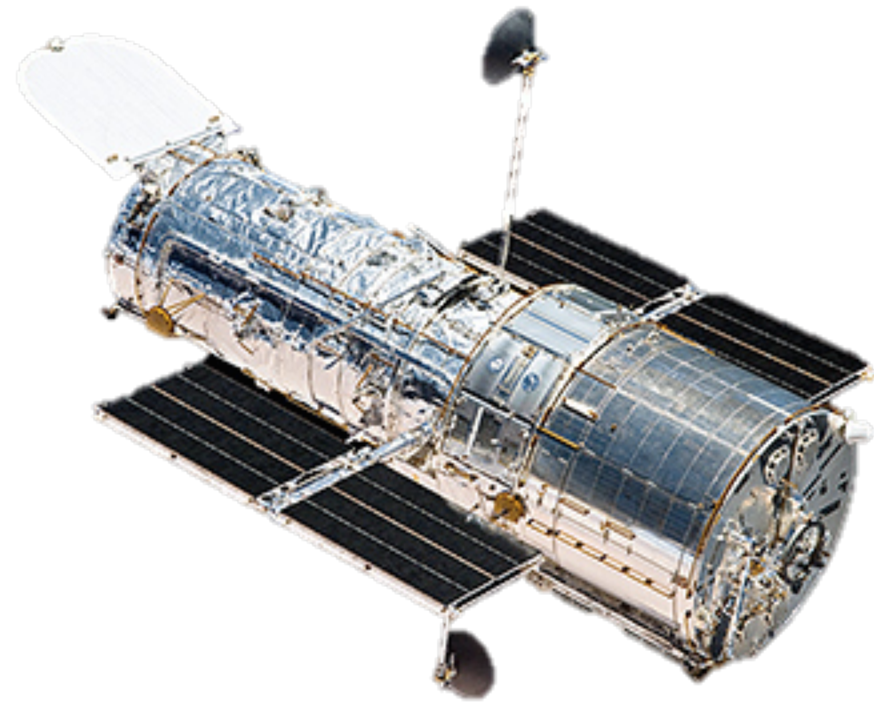
- Colors of stars in WFIRST field → temperature, extinction, metallicity
- WFIRST relative astrometry + GAIA absolute astrometry + HST colors → Detailed structure of the galaxy



IR HST (WFC3) Imaging

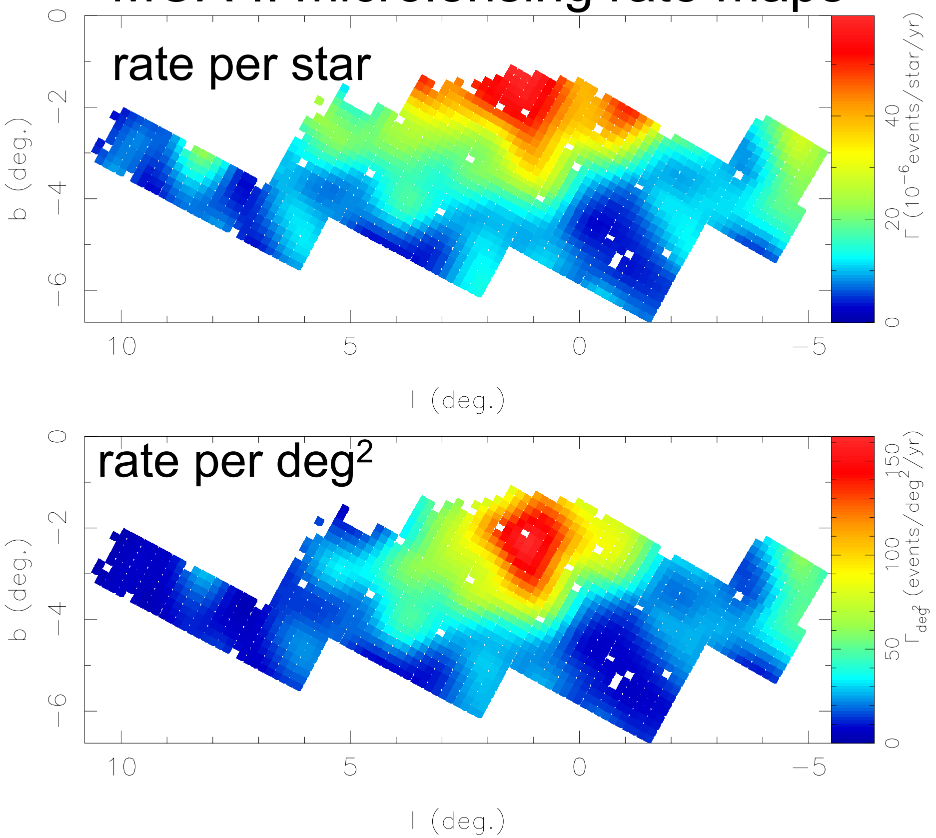
- Develop WFIRST exoplanet mass measurement method
- Help select WFIRST exoplanet microlensing fields

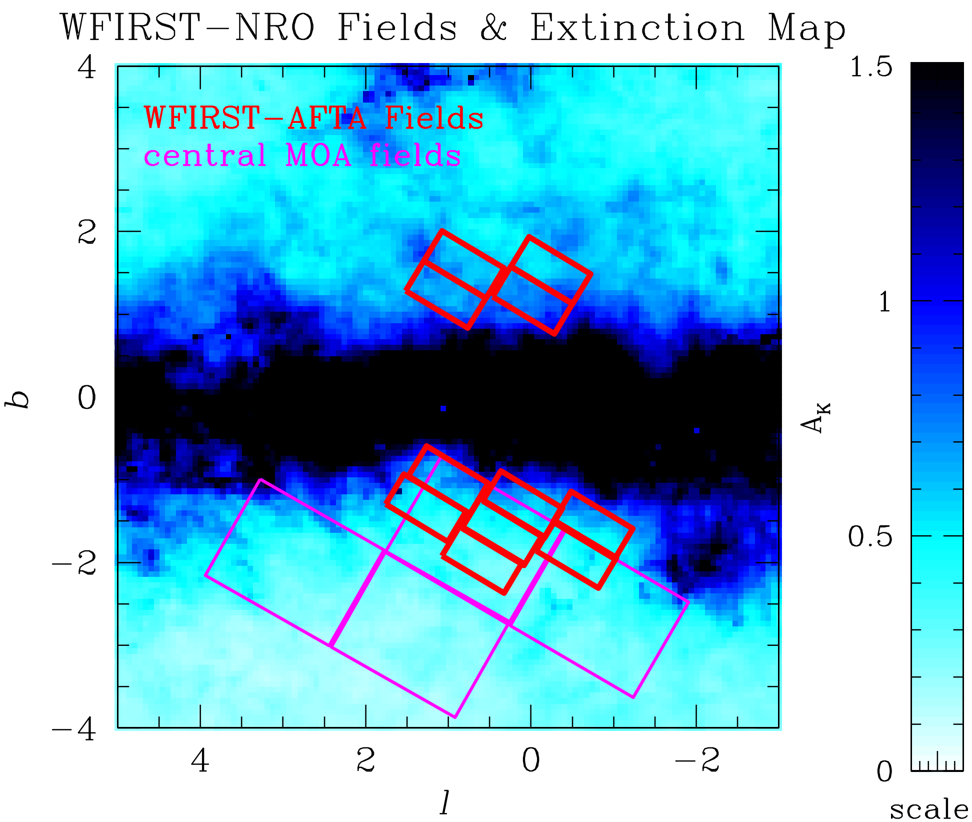
- Practice data for development of WFIRST exoplanet microlensing photometry/astrometry pipeline
    - critical for early science



Measure the Microlensing Rate in Target Fields with an IR Survey

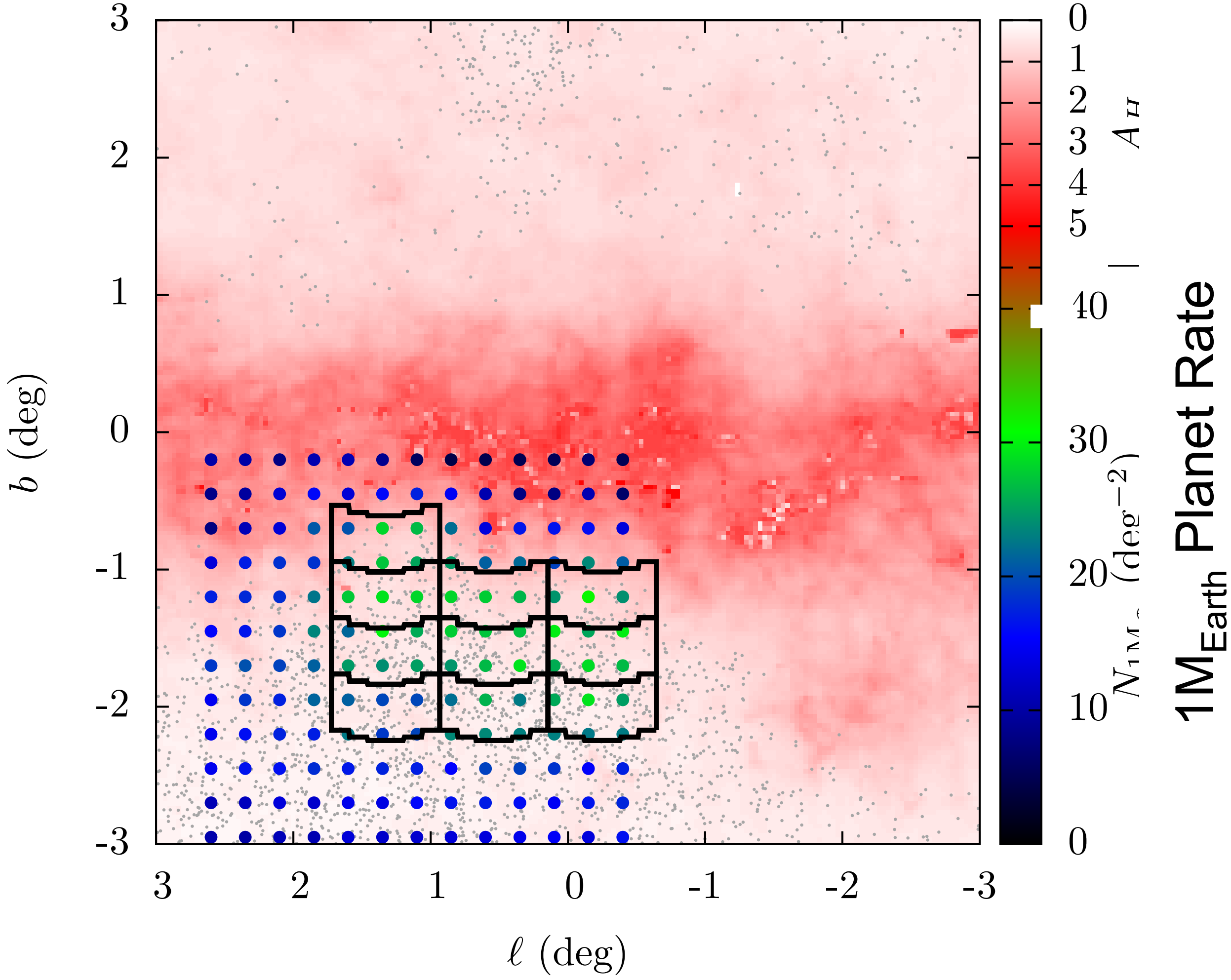
MOA-II microlensing rate maps





MOA-II measurements show maximum lensing rate at *l* = 1°, but this depends on extinction. Existing models are too simplistic to capture the detailed rate structure in *l* and *b*

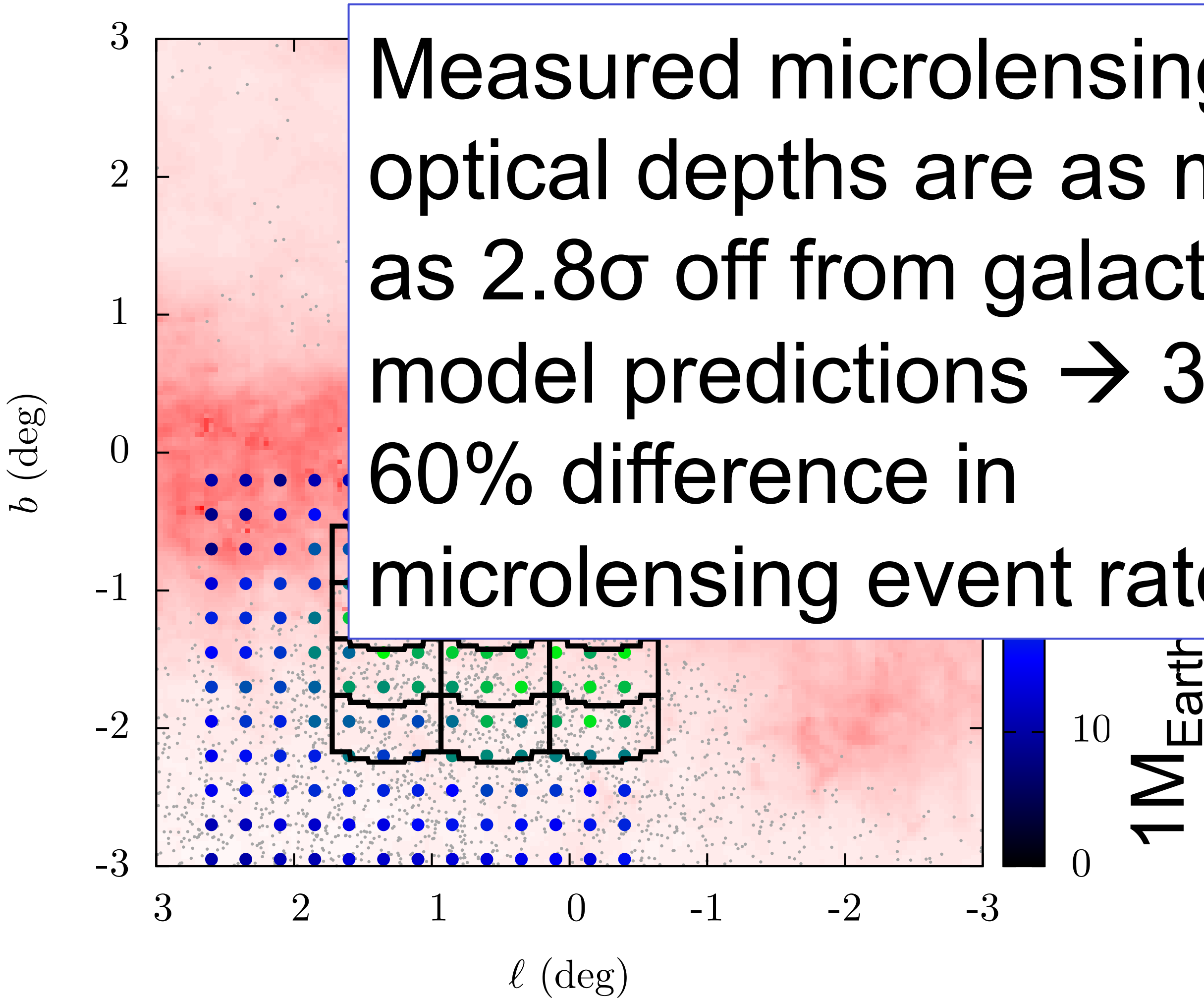
Ground-Based, Near-IR, Microlensing Survey



Tentative WFIRST field based on our current understanding, extrapolations, and assumptions.

Extinction map: Gonzalez et al. 2012

Ground-Based, Near-IR, Microlensing Survey



Measured microlensing optical depths are as much as 2.8σ off from galactic model predictions → 30—60% difference in microlensing event rates.

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assumptions.

Extinction map: Gonzalez et al. 2012

Major Observational Programs

- Directly support WFIRST science and reduce its scientific risk:
  - Early, optical, HST imaging of the WFIRST field
  - A preparatory, ground-based, microlensing survey in the near-IR
- Develop techniques for measuring (planet) masses:
  - Satellite parallax observations using Spitzer, Kepler, and TESS
  - HST or AO flux measurements of lenses in ground-based microlensing events
  - Measurements of microlens astrometry for black holes

Early HST Optical Observations of WFIRST Fields

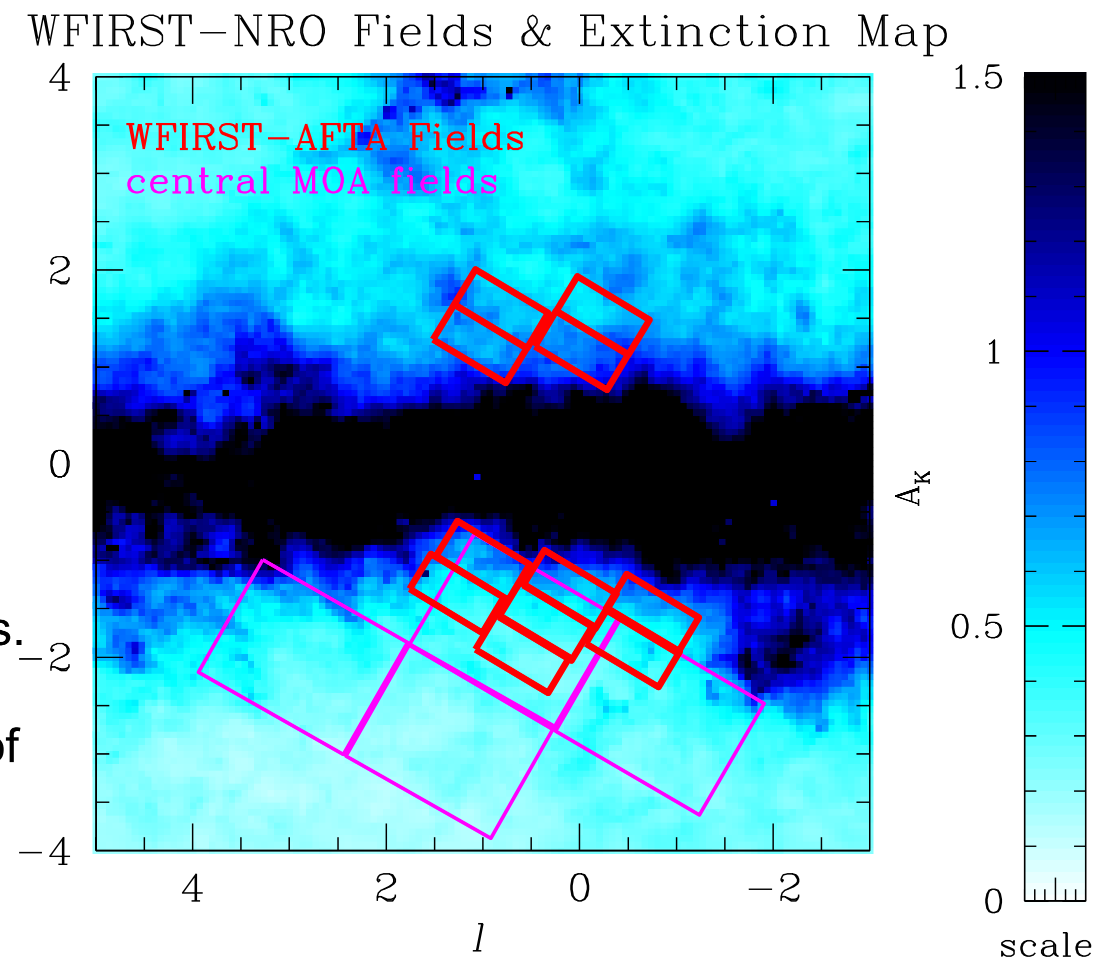
8-10 year time baseline

Relative proper motions for faint sources – resolved or nearly resolved in early observations

Long baseline for source proper motion – needed for astrometric microlensing

~750 orbits for all WFIRST ML fields.

A smaller program will allow a test of astrometry from WFIRST data, which has high S/N due to ~40,000 observations

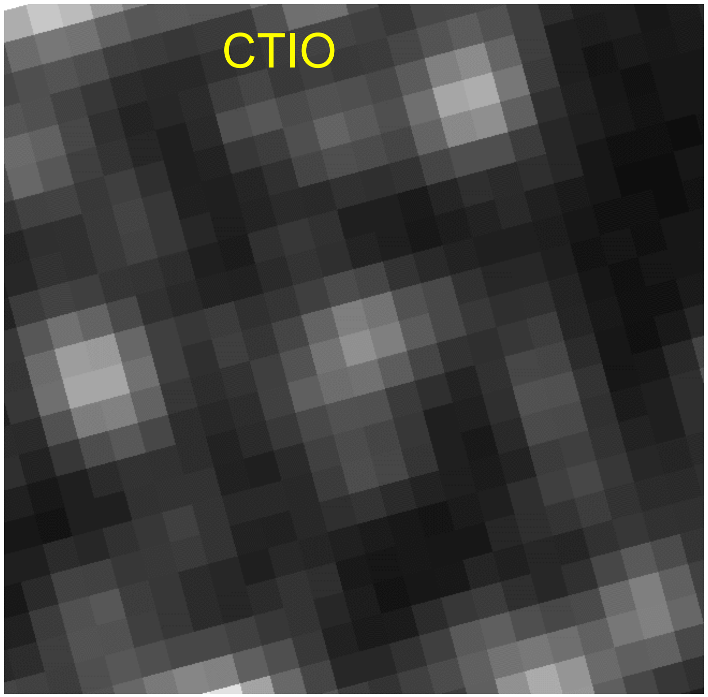


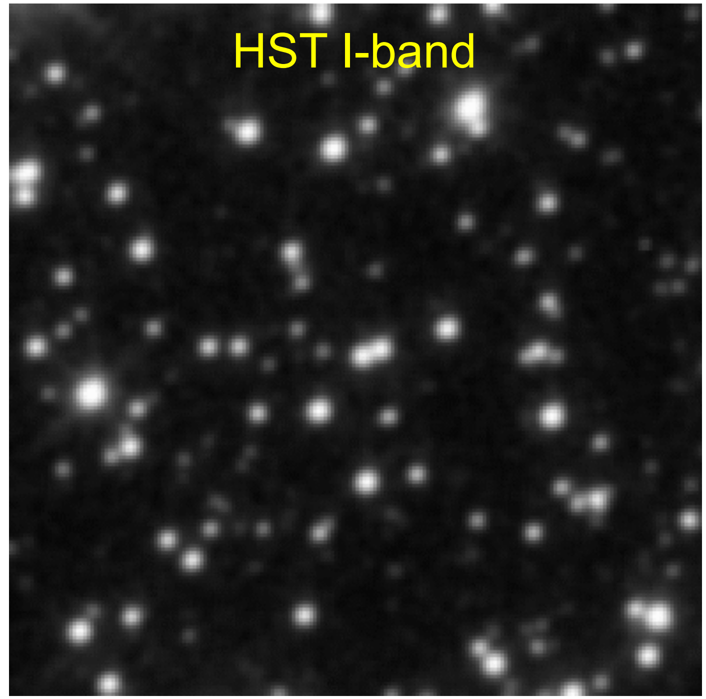
Ground-based IR Microlensing Survey

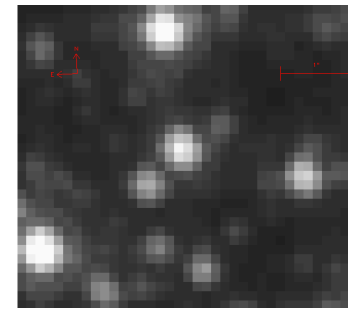
- WFIRST will go much deeper than a ground-based survey
  - We want to know how the lensing rate depends on source magnitude
  - Get rate of rare high magnification events => >1000 events

- VVV survey on Vista has too few observations
  - But telescope is capable if we could get a lot of time
- UKIRT
  - Need 2-3 hrs per night, 5 months per year for 3+ years
- Namibia Telescope
  - Sumi proposal (got to 2nd round this year)
  - H4RG detectors from WFIRST test program

New Photometry/Astrometry code needed



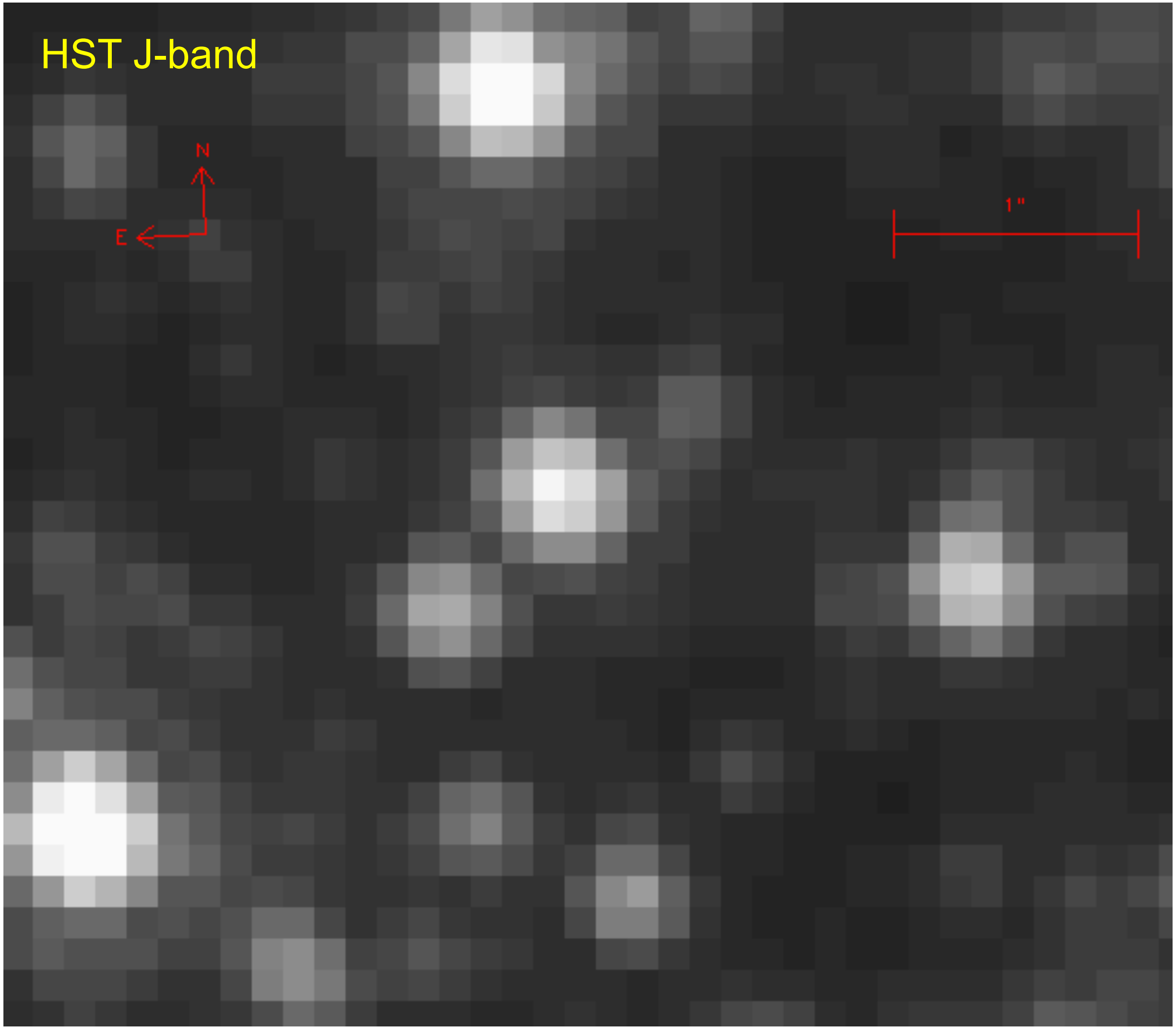




HST J-band

- These images are from MACHO fields with low extinction
- WFRIST-AFTA fields will be closer to the plane with 2-3 × the stellar density
- Proper motion of neighbor stars will be a significant source of photometry errors
- A time series of HST/WFC3/IR data will allow us to test photometry code

Blow-up of HST/WFC3/IR Image



Microlensing Survey Stars Will Not Be Isolated

- Proper motion of neighboring stars will contribute to photometry noise
- We want a WFIRST-AFTA exoplanet microlensing pipeline that generates
  - Photometry
  - Astrometry
  - A catalog of detector defects

- Develop exoplanet microlensing photometry+astrometry pipeline pre-launch using a time series of HST/WFC3/IR data
  - 3 epochs needed to get both proper motion and parallax

Microlensing Expertise

- Pre-2003 – microlensing yields only mass ratio and separation/R_E
- 2006 – lens identification and mass measurement from HST follow-up
- 2008 – microlensing can yield lens masses and orbital inclination
  - Microlensing parallax signals are stronger for binary and planetary events than for single lens events
- 2010-ish – circumbinary planet
- 2014 – planet in strong stellar binary system
  - perhaps some planets have been missed

- # of Dark Energy Scientists ≈ 10^2×(# of Microlensing Scientists)
  - Most major observing programs have no or only small US component
  - But US (ND and OSU groups) lead in microlensing theory & analysis

- Analysis of real data is key to developing expertise, so
  - More HST and Keck AO follow-up of planetary microlensing events
  - Satellite parallaxes with Spitzer, Kepler or other spacecraft far from Earth
  - Support of ongoing microlensing observing programs

Microlensing Manpower

- US microlensing community is small.
- Largely because of NSF funding issues. NSF will not fund telescopes or instruments beyond its own facilities
  - MACHO Project was funded by DOE and an NSF Center (outside the normal process)
  - Andicam instrument for CTIO – not a survey
  - SuperMACHO failed because it couldn’t get enough observing time (smaller telescope with more time would have been better).
  - LCOGT – but follow-up only
- Strategies for growing the US Microlensing Community
  - Extra support for students and postdocs
  - Extra support for research that broadens the community
  - Support for foreign microlensing surveys